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Risk Analysis for Earthquake-Damaged Buildings Using Point Cloud and BIM Data: A Case Study of the Daeseong Apartment Complex in Pohang, South Korea

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Abstract: Since 2016, the frequency and scale of earthquakes have been rapidly increasing in South Korea. In particular, the damage caused by the Gyeongju and Pohang earthquakes has attracted considerable attention since 2017, leading to changes in social insensitivity to safety and the perception of seismic damage to facilities. However, the current risk assessment technology for earthquake-damaged buildings is subjective and inaccurate, as it is based on visual inspection for a limited time. Accordingly, this study focuses on improving the method of analysis of disaster-damaged buildings. To this end, the study analyzes the risk factors of earthquake-damaged buildings by comparing point cloud data using 3D scanning technology with Building Information Modeling (BIM) spatial information, which is based on the existing design information. To apply this technology, existing design information was acquired through BIM modeling of the existing 2D design drawings of Building E in the Daeseong Apartment Complex (located in Heunghae-eup, Pohang City). This study is expected to contribute to improving the efficiency of measurement technology for earthquake-damaged buildings by analyzing old buildings' BIM-based 3D modeling visualization information without drawing information, and thus improving the accuracy of seismic damage risk measurement by scanning point cloud data.

Keywords: point cloud; building information modeling; earthquake-damaged buildings; 3D scanning; earthquake risk analysis

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1. Introduction

Since the late 1900s, the frequency and severity of natural disasters—including global warming-related events, storms, and floods—have been accompanied by an increase in the scale of damage. Over the last three decades, 2.5 million human lives have been lost worldwide as a result, leading to damage worth four trillion dollars [1].

In South Korea, this damage totals approximately 500 billion won, and an annual average of 1100 billion won has been spent on restoration over the last ten years (2006–2015). Specifically, property damage amounts to approximately 920 billion won on average per year [2]. Seismic damage has a tremendous impact on the overall national economy, as well as on the amount of damage and restoration costs in the affected area. As there have been more incidences of unpredictable natural and social disasters recently, thorough management and countermeasures need to be developed to prepare for them.

In particular, the frequency and scale of earthquakes have been rapidly increasing in South Korea since 2016; for example, much attention has been given to the damage caused by the Gyeongju and Pohang earthquakes since 2017, leading to changes in social insensitivity toward safety and the perception of seismic damage to facilities.

In an effort to minimize seismic damage, the National Disaster Management Research Institute first introduced the post-earthquake damage evaluation in South Korea in 2012 [3]. The main purposes of the evaluation were to quickly identify buildings' current status, establish appropriate countermeasures for the future, and prevent the economic losses that could arise from damage to the buildings.

The evaluation, however, has not been properly implemented because the evaluation system cannot cope with the unpredictability of seismic damage. Furthermore, due to manual evaluation methods and the lack of systematic management, the system is inefficient. In addition, considerable time is required to apply the evaluation [4].

In South Korea, New Zealand, and Japan, the current risk assessment technology for earthquake-damaged buildings is subjective and inaccurate due to limited visual inspection [5]. Currently, the emergency risk assessment in South Korea requires the state of each building to be assessed within four hours [3].

Thus, this study focuses on improving the analysis method that local governments with limited experience and personnel use to respond to earthquake-damaged buildings; the aim is to ensure that an effective emergency risk assessment can be conducted in the event of an earthquake. The technology facilitates the risk assessment of earthquake-damaged buildings by combining point cloud data with Building Information Modeling (BIM) data-based 3D spatial information.

Therefore, this study aimed to precisely analyze earthquake-damaged buildings' risk factors by comparing point cloud data based on 3D scanning technology with BIM spatial information based on existing design information.

To apply the developed technology, existing design information was acquired through BIM modeling of the existing 2D design drawings for the Daeseong Apartment Complex located in Heunghae-eup, Pohang City, which sustained the most severe damage of all the buildings damaged by the 2017 Pohang earthquake. In addition, the risk of the Daeseong Apartment Complex was analyzed by comparing point cloud data based on 3D scanning technology obtained through actual on-site measurements with BIM data-based 3D spatial information.

2. The Status of Seismic Damage in the Pohang Area and the Daeseong Apartment Complex

2.1. The Status of Seismic Damage in the Pohang Area

Since 2016, the frequency and scale of earthquakes have been rapidly increasing in South Korea. However, the proportion of buildings with seismic performance in South Korea's private sector is extremely low (approximately 33%) [6]. Given this, the occurrence of disasters, such as the Gyeongju and Pohang earthquakes, is highly likely to increase the volume of human casualties and economic damage. Compared with direct primary damage, such as the destruction of facilities, seismic damage may involve greater secondary damage due to the additional collapse of earthquake-damaged buildings caused by aftershocks.

According to the status of domestic and overseas earthquakes, as observed by the Korea Meteorological Administration [7] from 1999 (when digital earthquake observation began in South Korea) to 2016, there were 254 domestic earthquakes with a minimum magnitude of 2.0 in 2016, which is more than five times higher than the average number of domestic earthquakes before 2016, (i.e., 47). There were 34 earthquakes in 2016 that exceeded a magnitude of 3.0, which is significantly higher than the pre-2016 average of 9.4.

In this period, the domestic earthquake with the highest magnitude was the September 2016 Gyeongju earthquake, which had a magnitude of 5.8, closely followed by the November 2017 Pohang earthquake, with a magnitude of 5.4. In the case of the Pohang earthquake, a series of 44 earthquakes occurred in the 24 h after the main earthquake, resulting in the largest instance of seismic damage in South Korean history.

Due to the Pohang earthquake, 613 households had to move out of earthquake-damaged buildings, and there were up to 1797 evacuees per day due to aftershocks. According to a press release from the Central Disaster and Safety Countermeasure Headquarters of the Ministry of the Interior and Safety [8], the Pohang earthquake resulted in 92 human casualties, 123.5 billion won in total damage in Pohang, 27,000 damaged private facilities, 317 damaged public facilities, and 3174 reports (Table 1) [9].

Table 1. The status of earthquake-damaged facilities in Pohang.

Category	Facility		Unit	Damage (Million Won)	
				Quantity	Damage Amount
Total				27,317	55,057
Private facilities	Housing	Totally damaged	Building	331	9930
		Half damaged	Building	228	3420
		Partially damaged	Building	25,362	15,217
	Pens		Unit	24	21
	Etc.		Unit	1055	833
	Subtotal			27,000	29,421
Public facilities	School facilities		Unit	103	12,584
	Roads/bridges		Unit	2	930
	Port facilities		Unit	16	2414
	Cultural property facilities		Unit	14	1350
	Water and waste facilities		Unit	7	1709
	Landslides		Unit	7	436
	Repair facilities		-	5	454
	Sports facilities		-	9	1042
	Small facilities, etc.		-	154	4717
	Subtotal		-	317	25,636

2.2. The Status of Seismic Damage in the Daeseong Apartment Complex in Pohang

The Daeseong Apartment Complex, located in Heunghae-eup in Pohang City, is a corridor-type five-story apartment complex built in 1988. It consists of six buildings and 260 households. The Daeseong Apartment Complex was selected as a target building for seismic risk analysis in this study as it sustained the most damage in the Pohang area. As a case study, Building E was selected, and an on-site scanning analysis was conducted.

Among the six buildings of the Daeseong Apartment Complex, the use of Buildings D, E, and F was restricted after the occurrence of the Pohang earthquake, and they were demolished in March 2020. In the case of Building E, which sustained the most damage, precision inspection results showed that more than half of the building ground was inclined due to damage to the walls that were in contact with the ground as shown in Table 2 and Figure 1 [10].

Table 2. Information and damage status of the target building (the Daeseong Apartment Complex).

Target building	Entire area around Building E in the Daeseong Apartment Complex in Pohang
Address	7 Handong-ro Heunghae-eup Buk-gu Pohang City, Gyeongsangbuk-do
Number of households	260 (6 buildings)
Main structure	Reinforced concrete structure
Area (m^2)	5 stories, distributed across 50 m^2 and 60 m^2
Completion/move-in	December 1987/December 1988
Damage status	– Subjected to the most damage among private facilities in Pohang – Distance from the epicenter: 2.1 km – The use of 3 buildings (170 households) out of 6 was restricted. Building E was demolished (March 2020). – More than half of the ground of Building E was inclined due to damage to the walls that were in contact with the ground. – Shear failure occurred in 13 out of the 55 columns on the basement floor.

(**a**) (**b**)

Figure 1. Separated joint, impact fracture, joint fracture, and short column fracture in the Daeseong apartment complex. (**a**) Separated joint, impact fracture; (**b**) Short column fracture on the basement floor.

3. Analysis Methodology

3.1. Characteristics of 3D Laser Scanning and Point Cloud Technology

Laser scanning technology uses a measurement technology referred to as light detection and ranging (LIDAR) or laser detection and ranging (LADAR). This represents an object as a set of 3D coordinates by scanning a laser beam from a measuring instrument to the object at regular intervals, and using the direction and measurement distance of the beam reflected from the object [11,12]. In addition, the set of 3D coordinates reflected from the object is referred to as a point cloud. Based on this, design and construction errors were reviewed and analyzed. If the laser beam from a measurement point is not received, however, the information on the point cannot be identified. Therefore, preliminary examination and planning for point cloud acquisition are extremely important [13].

3.2. Building Analysis Method: Combining Point Cloud Data and 3D Spatial Information

3D laser scanners can generally be categorized under either the time of flight (TOF) method, which measures the laser's arrival time, or the triangulation method, which performs triangulation using the distance between the laser transmitter and the receiver, depending on the operation method. The TOF method is usually used in the construction field. In addition, the acquired point cloud can be used for various analyses, such as the building's consistency and verticality, as well as quantity estimations [14]. However, this study focused on the analysis of smoothness among building risks. According to the principle of building smoothness analysis based on the point cloud, the reference levels of members, such as floors, walls, and ceilings, are set using the acquired 3D coordinates, and the coordinate values (x, y, z) that deviate from the references are analyzed [15]. In addition, the smoothness levels of individual members can be intuitively determined using the legend.

3.3. Point Cloud Field Analysis Procedure

Building risk analysis based on point cloud data and BIM, which was introduced in this study, enables data extraction and modeling for the identification of critical members through rapid scanning [16]. The detailed procedure and definitions for the analysis of the risks associated with Building E in the earthquake-damaged Daeseong Apartment Complex are as follows Table 3 [17,18]:

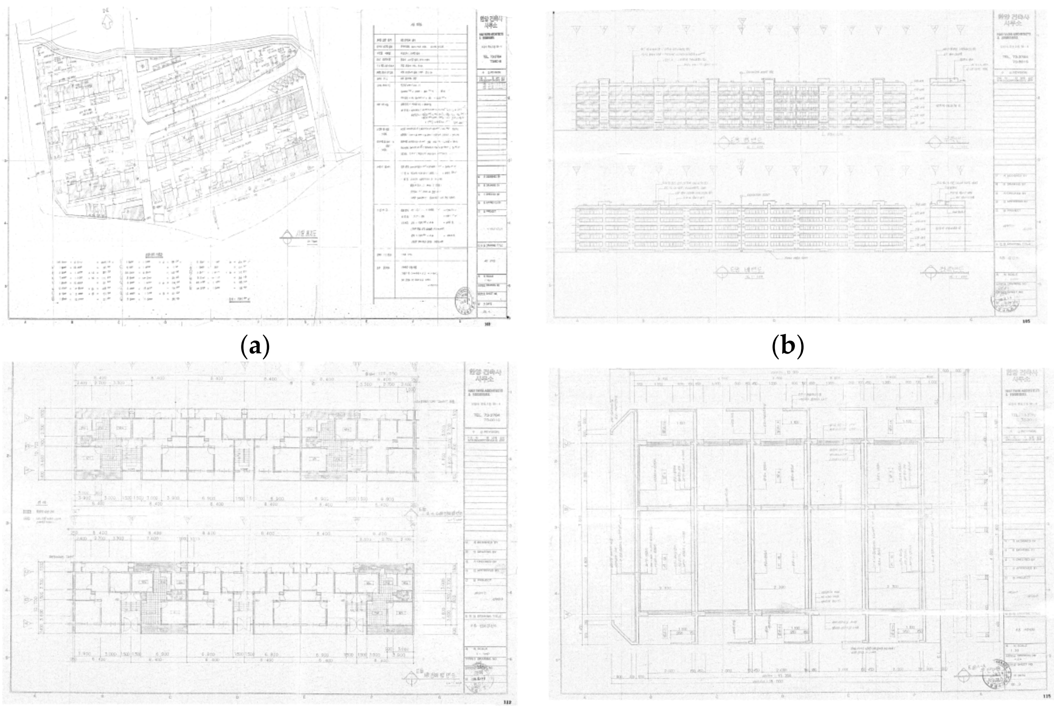
Table 3. The process and measurement time for analyzing the risks of seismic damage to Building E, based on the point cloud.

Process	Measurement Time
① Equipment setting (3D scanner installation and setting) 3D scanners are set at Stations 1, 2, 3, 4, and 5 to conduct emergency risk assessment using the point cloud system.	①–③: Measurement Process 27 min 35 s
② Review of measurement points 3D scanners are installed after reviewing appropriate measurement points for scanning the building's exterior. Measurement points are installed at stations 1, 2, 3, 4, and 5, considering the characteristics of the 3D scanners. (5 stations measurement).	
③ Building exterior measurement The building's exterior is scanned and measured using 3D scanners.	
④ Point cloud data extraction After moving to the site for the analysis of the collected point cloud data, the data are extracted.	④–⑤: Analysis Process 30 min 50 s
⑤ Information encoding and precision analysis The target building's damage situation is analyzed in detail using the extracted point cloud data.	

4. Risk Analysis of an Earthquake-Damaged Building Using Point Cloud and BIM Data

4.1. Reverse-Engineering a Building's 3D Geometry Using BIM Data Modeling

For the BIM modeling of the target building, the hand-drawn pdf files were analyzed and converted into BIM modeling files. The target building, which was completed in 1987, does not have 2D drawings (dwg), only hand-drawn drawings as image (pdf) files as shown in Figure 2.



(a) (b) (c) (d)

Figure 2. Layout of the Daeseong Apartment Complex and drawings of Building E. (**a**) Layout of the complex; (**b**) Elevation of Building E; (**c**) Floor plan of Building E; (**d**) Sectional view of Building E.

Several repairs and interior changes since the completion of the target building in 1988 have changed its elevation. In this study, BIM modeling was performed based on the first drawings as shown in Figure 3. 3D information could be compiled using 2D information through BIM modeling, and an analysis was conducted in connection with the 3D scanning data that was acquired later.

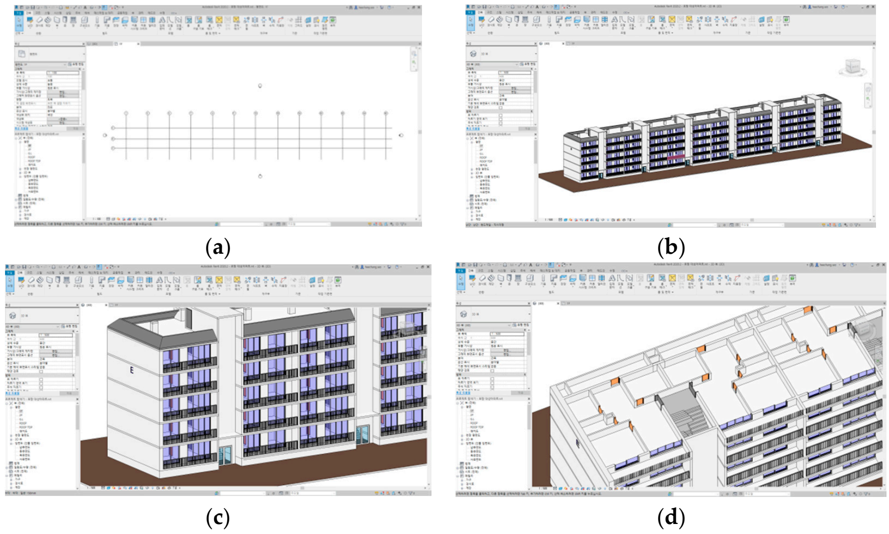


Figure 3. BIM modeling of the Daeseong Apartment Complex through reverse engineering of 3D geometry. (**a**) Grid setting for the BIM modeling of Building E; (**b**) BIM modeling of Building E; (**c**) Elevation of Building E; (**d**) Sectional view of Building E.

4.2. On-Site Data Extraction through the Point Cloud

For an earthquake-damaged building, it is highly likely that over time, the internal strength will have decreased and there will be external deformation, such as the dropout and deformation of members. In this study, as shown in Figure 4, the earthquake-damaged building's external smoothness and slope were analyzed by combining the point cloud data acquired through 3D scanning with spatial information as a verification case. In addition, the risk of cracking and deformation was analyzed for the building's non-structural elements, and the smoothness of the surrounding ground was analyzed to examine the topographic characteristics around the target building.

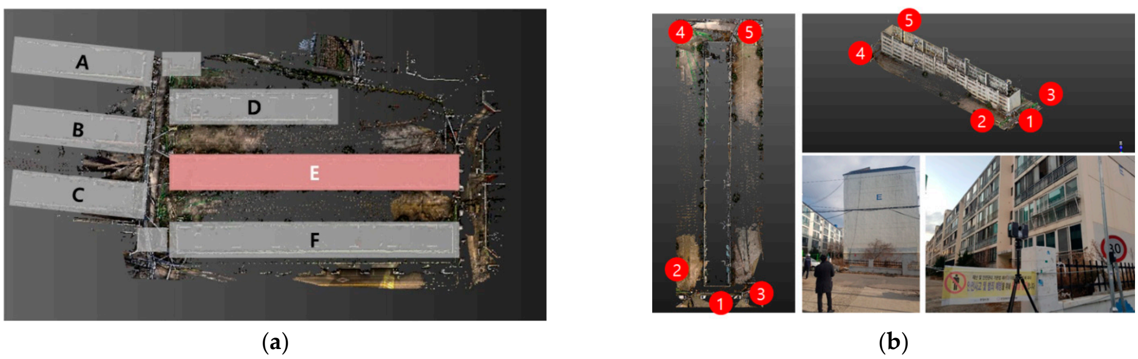


Figure 4. Field design for scanning the Daeseong Apartment Complex. (**a**) Location of Building E in the Daeseong Apartment Complex. A–F is the number of buildings in apartments; (**b**) Scanning measurement locations and on-site analysis. ①–⑤ is measurement points of the 3D scanner in on-site.

On-site analysis of the target building's risks spanned five hours, beginning at 12:00 on 18 December 2019. This analysis was primarily conducted on Building E, which sustained the most severe damage of the six buildings in the apartment complex as shown in Figure 5. The 3D scanning analysis was conducted around Building E to analyze the smoothness of the surrounding ground, as well as cracks, deformation, and dangerous falling objects.

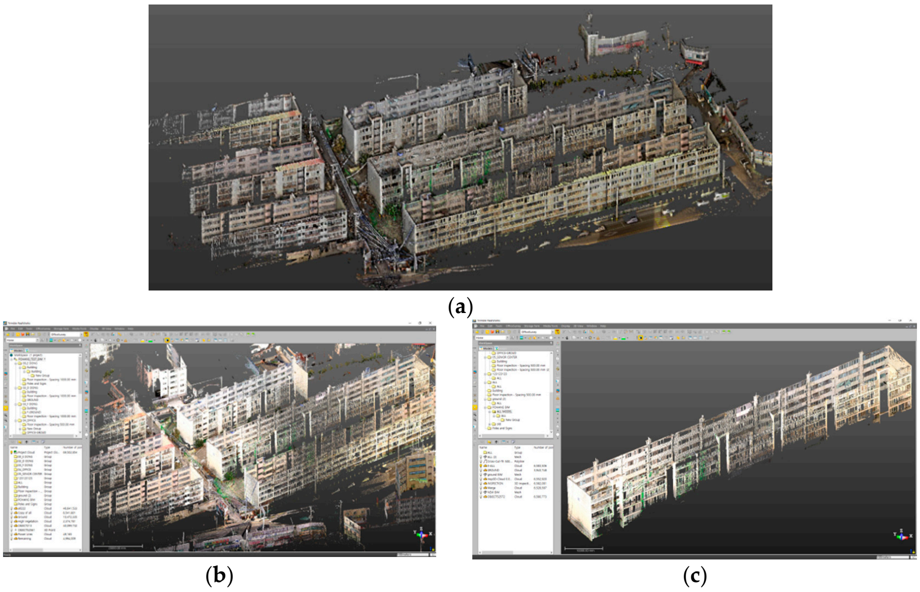


Figure 5. Analysis using only 3D scanning data. (**a**) Point cloud data for the Daeseong Apartment Complex; (**b**) Acquisition of point cloud data; (**c**) Extraction of Building E data.

4.3. Combination of Point Cloud and BIM Data

To analyze the risks of seismic damage to the Daeseong Apartment Complex, the data were combined so that the point cloud and BIM data could be located at the same coordinate values. Although the same coordinate values must be used to combine the two datasets, the corner points of the structure were set as the data combination reference points due to the loss of reference points. The images below show the combination of the two datasets without further analysis.

The blue color shown in Figure 6 is the point cloud obtained by scanning the building E of the Daeseong Apartment Complex, therefore representing the actual damage after the earthquake. The gray color reflects the undamaged status through a BIM model based on the 2D drawings. Figure 6d,e shows the result of combining the two kinds of data, and the colored part shows a mismatch.

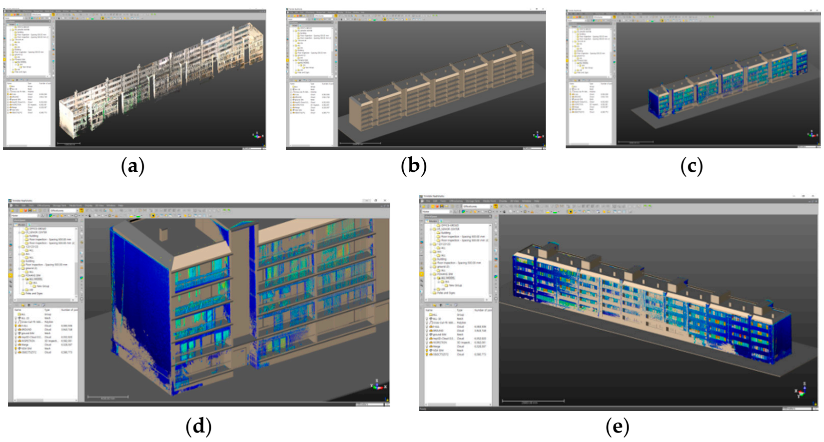
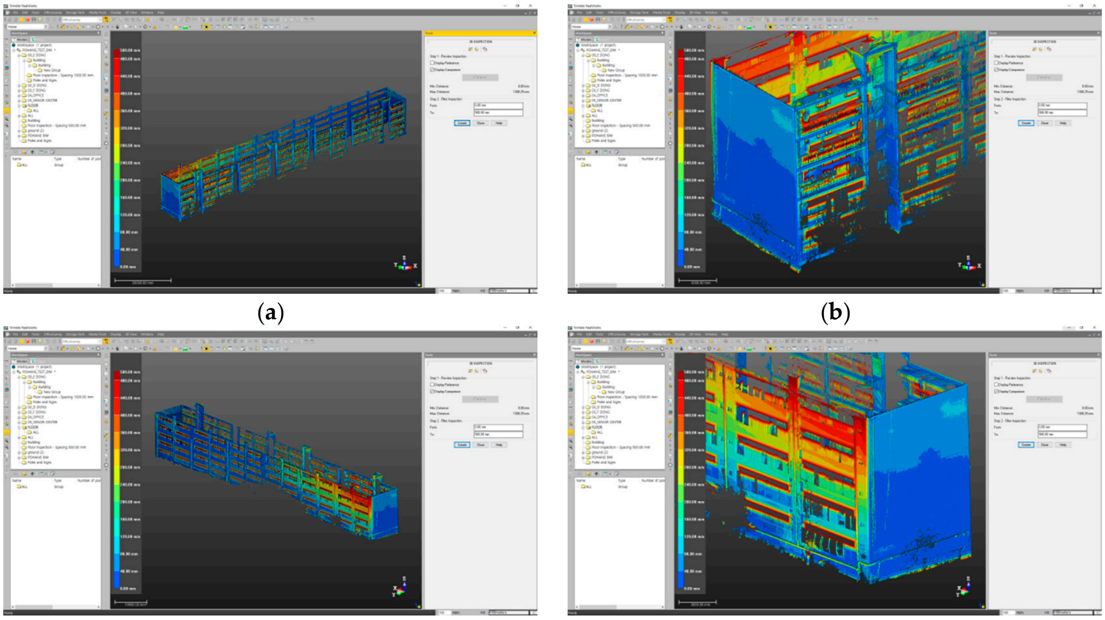


Figure 6. Combination of the point cloud and Building Information Modeling (BIM) data for existing drawings of Building E. (**a**) Point cloud data for Building E; (**b**) BIM data for Building E; (**c**) Data combination; (**d**) Point cloud data combined with BIM data; (**e**) Point cloud data combined with BIM data.

4.4. 3D Inspection Using Point Cloud and BIM Data

3D inspection was performed using the point cloud data acquired through 3D scanning and the BIM data modeled using the drawing information [19]. 3D inspection refers to the analysis of the two datasets based on the same coordinate values that were used to identify differences in the overall geometry [20]. In this study, the BIM data were used as a source of information before the seismic damage occurred, while the point cloud data were used as a source of information after the occurrence of seismic damage.

Figure 7 shows the numerical results of inspection through scanning data and BIM data. The analysis results set the legend from blue to red. To explain the meaning of the colors, the blue series means that the two data differ by 0 to 80 mm, the green and orange series by 150 to 360 mm, and the red series by 360 to 500 mm. This analysis effectively provides a quantitative value for the degree of earthquake damage in building E.



(**a**) (**b**) (**c**) (**d**)

Figure 7. 3D inspection using the point cloud and BIM data. (**a**) Entire 3D inspection; (**b**) Front 3D inspection; (**c**) Rear 3D inspection; (**d**) Rear 3D inspection in detail.

5. Discussion of Findings

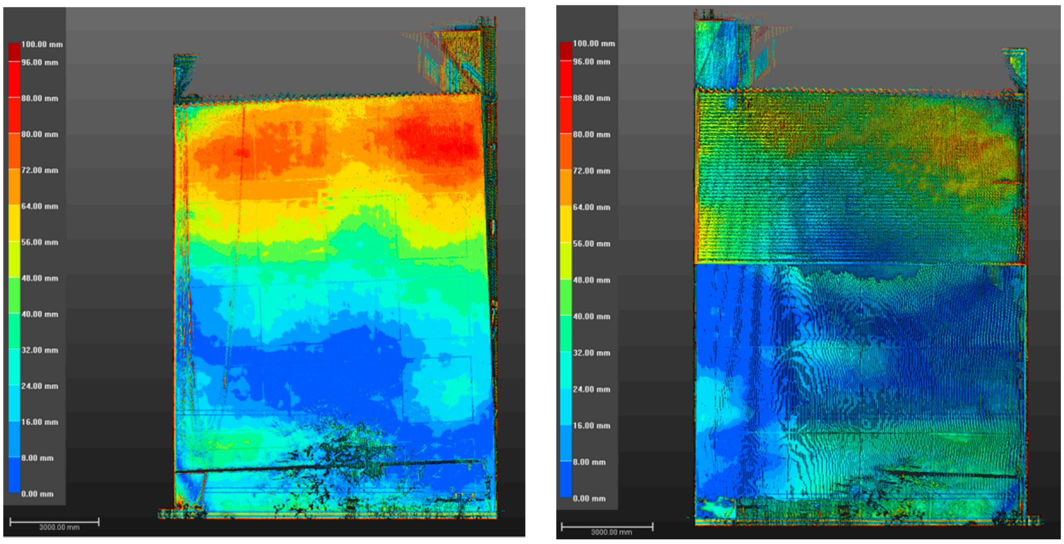
The risks associated with Building E in the Daeseong Apartment Complex were analyzed using modeling spatial information by combining point cloud and BIM data based on the existing design information. The analysis results are as follows.

5.1. Analysis of Wall Smoothness on the East and West Sides

A risk analysis was conducted by analyzing the smoothness of the building's east and west walls using the combined point cloud and BIM data as shown in Figure 8. For the analysis of the smoothness of the walls, the flatness of the walls was analyzed by combining the 3D measurement point information gathered from the point cloud data for Building E's side walls, as measured using 3D scanners with BIM information based on the existing design information. In addition, the information was used to analyze the overall deflection of the building's outer walls, as well as the deformation and displacement of the vertical and transverse cross-sections as visual data.

Figure 9 shows the smoothness analysis results for Building E's east and west sides. Significant differences in displacement between the upper and lower parts of the building E's west side were observed. The difference was found to be a maximum of 35 mm (from 0 to 35 mm) in the lower part and 84 mm (from 40 to 84 mm) in the upper part, indicating that the deformation of the building occurred as a result of the lateral force exerted by the earthquake on the vulnerable side.

Figure 8. Spatial information analysis of Building E's outer west wall.



(**a**) (**b**)

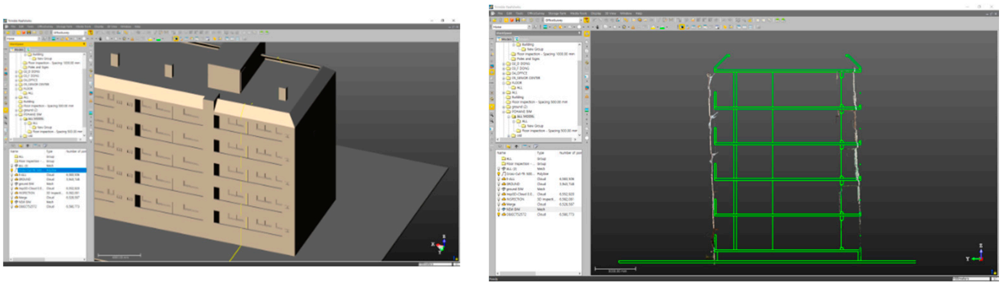
Figure 9. Smoothness analysis results for Building E's east and west walls. (**a**) Analysis of Building E's west wall; (**b**) Analysis of Building E's east wall.

5.2. Analysis of Building E's Overall Slope

The lines of the desired cross-sectional areas were extracted from the BIM data, and the overall slope of the building was measured by comparing them with the point cloud data. The above wall smoothness analysis results revealed a significant change in the displacement of the west wall, which shows that the building was inclined backward. Therefore, the side slope of the building was analyzed in detail as shown in Figure 10.

As follows Figure 11, the overall analysis of the east and west walls showed that the building was inclined by 2.09° and that the upper part of the wall was inclined forward by 88 mm compared to the lower part. This is because there was no internal column and only the walls were designed to bear the load of the Daeseong Apartment Complex ground floor.

Thus, the walls, which were constructed by stacking bricks, were vulnerable to seismic loads due to insufficient wall volume caused by the weak Rahmen structure.



(**a**) (**b**)

Figure 10. Analysis of Building E's slope. (**a**) Extraction of cross-sectional information from BIM data; (**b**) Results of examining Building E's overall slope.

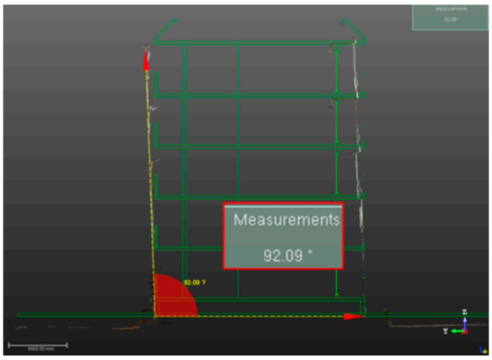


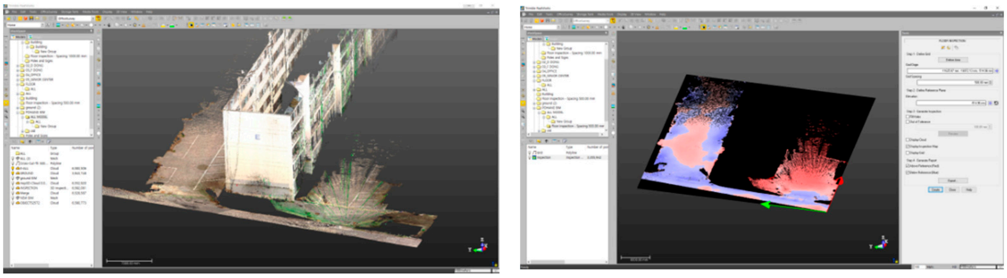
Figure 11. Slope analysis results for Building E.

This phenomenon resulted from the apartments' unique structure; that is, the Daeseong Apartment Complex was constructed without the application of seismic design, and it appears to have been affected by the piloti structure, in which the ground floor's load-bearing walls are supported by the short lower columns. The ground floor structure was supported only by pilotis, because it was not connected to the underground outer walls, and the pilotis were classified as short columns due to the underground pit level's low floor height. The slope appears to have been caused by the short column phenomenon of the pilotis, which completely collapsed under the force of the earthquake due to structural vulnerability. These results were analyzed in the same way as the nonlinear dynamic analysis according to the Committee of Site Inspection and Damage Investigation's "Site inspection and damage investigation of buildings by earthquakes in Gyeongju and Pohang" report [10].

In addition, the Ministry of Land, Infrastructure, and Transport (MOLIT) specifies safety grade standards for structures under the Special Act on Safety Management of Facilities (from Grade A to E) [21]. According to these standards, Grade D and E reflect very dangerous damage to the structure. Grade D is about 0.38° (within slope 1/150); and Grade D and E entail closed or restricted building use for safety purposes.

5.3. Analysis of the Ground Smoothness around Building E

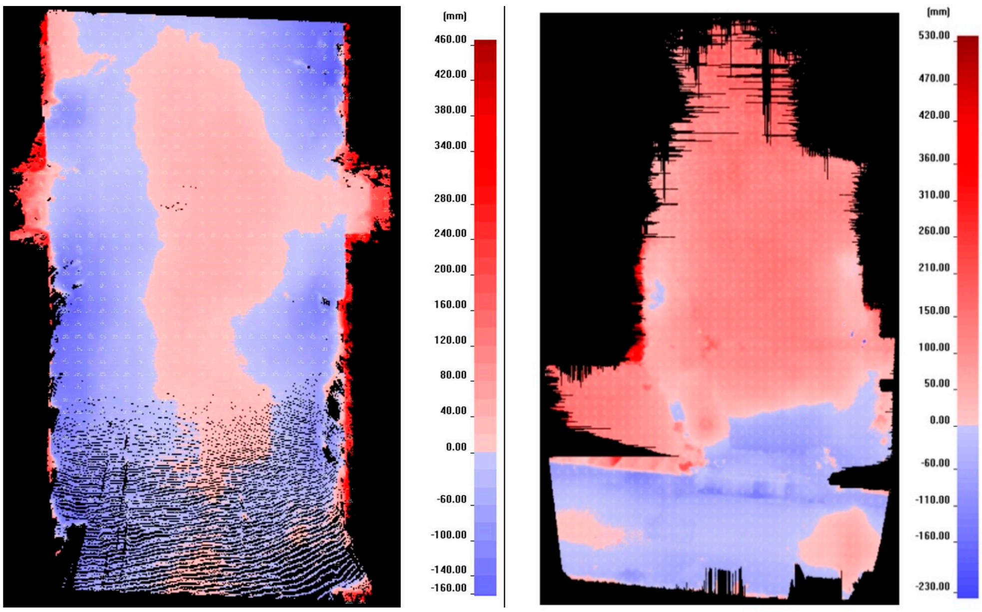
The ground smoothness at the front and back of Building E was analyzed to determine the risk associated with the terrain surrounding the Daeseong Apartment Complex based on the point cloud data as shown in Figure 12.



(**a**) (**b**)

Figure 12. Analysis of the front and back of Building E. (**a**) Roads around Building E; (**b**) Analysis of the roads around Building E.

The ground smoothness analysis results for Building E showed that there was a difference in displacement between the terrains around the building as shown in Figure 13. There was a 620.00 mm difference between Buildings E and D (from 460.00 to −160.00 mm) and a 760.00 mm difference in front of Building E (from 530.00 to −230.00 mm), indicating that changes in terrain displacement occurred due to ground subsidence caused by the earthquake.



(**a**) (**b**)

Figure 13. Smoothness analysis results for Building E's surrounding area. (**a**) Smoothness analysis result between Buildings E and D; (**b**) Smoothness analysis result in front of Building E.

It appears that a number of structures in the surrounding area were overturned, and the topographic change around the building was intensified by the 44 aftershocks that followed the first major earthquake. The Korea Institute of Geoscience and Mineral Resources analyzed the Heunghae-eup area in 2017 and found that it sustained the most damage due to the severe impact of ground subsidence, which corresponded to the active fault in the marine sediment created in the tertiary period.

6. Conclusions

To account for the shortcomings of current emergency risk assessments, which are operated as a post-damage management system for earthquake-damaged buildings, this study aimed to perform a detailed analysis of the risk of the earthquake-damaged Daeseong

Apartment Complex in Pohang. This was achieved by combining point cloud data based on 3D scanning technology with 3D spatial information. When the target building case analysis was applied to the seismic damage risk assessment, an attempt was made to examine the appropriateness of the building risk prediction direction to effectively analyze and reflect the modeling information combination according to the optimal point cloud data and 3D spatial information. Consequently, 3D scanning technology was applied to the existing earthquake-damaged building, and the following practical analysis results were derived.

First, for the wall smoothness analysis, the overall deflection of the building's outer walls, as well as the deformation and displacement of the vertical and transverse cross-sections, were analyzed as visual data. The smoothness analysis results for the west side of Building E revealed that there was a large difference (with a maximum of 84 mm) in the displacement between the building's upper and lower parts. This indicates that the building was deformed due to its vulnerability and the side lateral force caused by the earthquake.

Second, the slope of Building E's left side was analyzed based on the actual measured point cloud data. The analysis results showed that the building's overall inclination was 92.09°, indicating a slope of 2.09°. This suggested that the structure was damaged by excessive subsidence or uneven settlement in the Daeseong Apartment Complex's foundations (i.e., in the ground).

Third, the ground smoothness behind Building E was analyzed to determine the risk associated with the terrain surrounding the target building based on point cloud data. The analysis results showed that there was a difference in the displacement between the terrains around the building that ranged from 620.00 mm to 760.00 mm. This indicates that changes in terrain displacement occurred due to building ground subsidence caused by the earthquake.

By providing 3D modeling visualization information and improving the accuracy of risk assessments for actual earthquake-damaged buildings, the risk assessment technology developed in this study is expected to contribute to improving the inefficient measurement methods of existing assessment technology. Future research should conduct a study on this assessment system with a focus on its consistency with existing assessments, and its appropriateness in terms of the assessment classification system.

Furthermore, the development of this technology for multidimensional interdisciplinary models, in addition to being a post-damage management system for earthquake-damaged buildings, should be considered in order to expand the value of this research in the future. In terms of related technology development, this study focuses on the risk management of historical properties [22,23] and energy saving [24] cases of old buildings using BIM. The use of point cloud and BIM data is also expected to be an appropriate methodology to measure the value of current buildings.

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