Digital twin-based investigation of a building collapse accident

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Abstract

The collapse of engineering structures can cause significant casualties and have negative social effects. Collapse accident investigation can elucidate the potential causes and mechanisms of the collapse accident, thus remediating future structural collapse and enhancing the resilience. However, there are some obstacles to investigating complicated collapse accidents using conventional methods. For example, the out-syncs between on-site investigation and simulation analysis are intractable and can make discovering the cause of collapse accidents difficult. Hence, a digital twin-based investigation method for collapse accidents was proposed. First, basic virtual digital building models are established using real-world information. Then, after mapping the data from the real world into the virtual space, the corresponding highly realistic multistage models before and after the building collapse accident are constructed and synchronized. Using the digital twin method, investigators with multidisciplinary knowledge can efficiently integrate, update, and check the models. Finally, the potential collapse mechanism was revealed with the assistance of the corresponding models. To demonstrate the effectiveness of the proposed digital twin-based investigation method, a real collapse accident investigation is utilized as an example. These results validated our method.

Keywords

digital twin (DT), building collapse investigation, building information modeling (BIM), finite element analysis (FEA), collapse simulation.

1. Introduction

Safety during the service life is one of the most critical building requirements. However, in the last few decades, building collapse accidents have repeatedly occurred worldwide, causing severe injury, death, adverse social impact, and economic loss [1-4]. These catastrophic events have raised increasing concerns for engineers and researchers. To ensure integrity and safety, it is essential to analyze the potential causes of collapse, which will, in turn, provide valuable references for building design, construction, and maintenance, as well as collapse-prevention strategies.

Building collapse can be caused by several factors, making it difficult to identify the major causes [5-8]. Widely used building collapse investigation methods include (1) site-investigation methods [9, 10] and (2) simulation-based methods [4, 8]. Although widely used, these investigation methods are limited in more complex situations. Specifically, the site investigation method can hardly reproduce the collapse scenario of a building. The motion of fragments determines the distribution of the debris, which is crucial for accident investigation [11]. As for simulation-based methods, the result of collapse analysis relies on quantifying uncertainties in building modeling [12]. An effective method for reducing the modeling uncertainties is updating the design document-based FE model with real-time measurement data [12]. However, the out-syncs between the on-site investigation and simulation-based analysis are intractable and can cause difficulties in determining the causation of collapse accidents. For the above reasons, new digital methods, combining site-investigation and numerical methods, need to be proposed to assist the investigation.

The digital twin concept originated from Michael W. Grieves's product lifecycle management model in 2002 [13]. A digital twin is a set of virtual information constructs that fully describes a potential or actual physical entity from the micro atomic to macro geometrical level [13]. The foundations of a digital twin can be divided into four parts: (1) modeling and simulation of a physical entity to build the corresponding virtual entity and connections; (2) data collection and data fusion for physical, virtual, and fusion data between them; (3) interaction and collaboration between the physical and virtual entities; and (4) relevant theories of service [14]. The digital twin is a fast-evolving technology, and many researchers have explored its application in the smart manufacturing [15-16] and automated product-service systems [17]. Nowadays, the digital twin technology has expanded to the civil engineering sector [18]. Liu et al. [19] established a digital twin multidimensional model of prestressed steel structures for the safety risk assessment of prestressed steel structures. Peng et al. [20] reported a digital twin system of a hospital, by which the quality of daily maintenance work was enhanced. Lu and Brilakis [21] delivered a slicing-based object-fitting method that can generate the geometric digital twin of an existing reinforced concrete bridge from a labeled point cluster. Shim et al. [22] developed a bridge maintenance system for prestressed concrete bridges using a 3D digital twin model. Angjeliu et al. [23] studied the structural system integrity of historic masonry buildings by developing the concept of digital twins. The digital twin can also be used in retrofitting and demolishing because of its ability to comprehensively characterize the building to be renovated [24]. Previous studies have shown that, with the help of a digital twin, researchers can obtain a comprehensive understanding of the building and establish high-fidelity 3D models for simulation and mechanical calculation. Therefore, the digital twin has the potential to become an effective tool for analyzing the cause of building collapse.

In this study, a digital twin-based building collapse investigation method is proposed. Digital twin-based collapse analysis techniques have been proposed and used to simulate the entire life cycle of a building and then reproduce the building collapse accident. Specifically, building information models (BIM), finite element models (FEM), and physics engine models of the building were established to simulate the performance of the building during operation and maintenance. Subsequently, the main causes of building collapse were analyzed and expounded. The results indicate that defects or damage in critical regions of buildings are important factors that can cause building collapse. The rationality of the digital twin-based virtual model analysis was validated by site investigation. The results show that digital twin techniques are powerful tools for analyzing the cause of building collapse.

2. Digital twin-based collapse investigation method

It is difficult to effectively determine the cause of building collapse using traditional analysis methods, such as on-site investigations and surveillance videos. Hence, this study proposed a digital twin-based collapse investigation method to elucidate the causes of building collapse. Figure 1 presents the conceptual architecture of the digital twin-based collapse investigation method, which considers the critical changes throughout the building life cycle (i.e., from construction to collapse). The digital twin model consists of two components: physical models (in the real world) and virtual models (in digital space). The building information was continuously exchanged between the two models. Specifically, the interaction between the physical and virtual spaces involves three steps: Step 1 data collection and modeling, Step 2 construction and updating, and Step 3 on-site investigation and simulation. Furthermore, the workflow of the proposed digital twin-based method incorporating physical models, building information models (BIMs), and finite element models (FEMs) are briefly presented below.

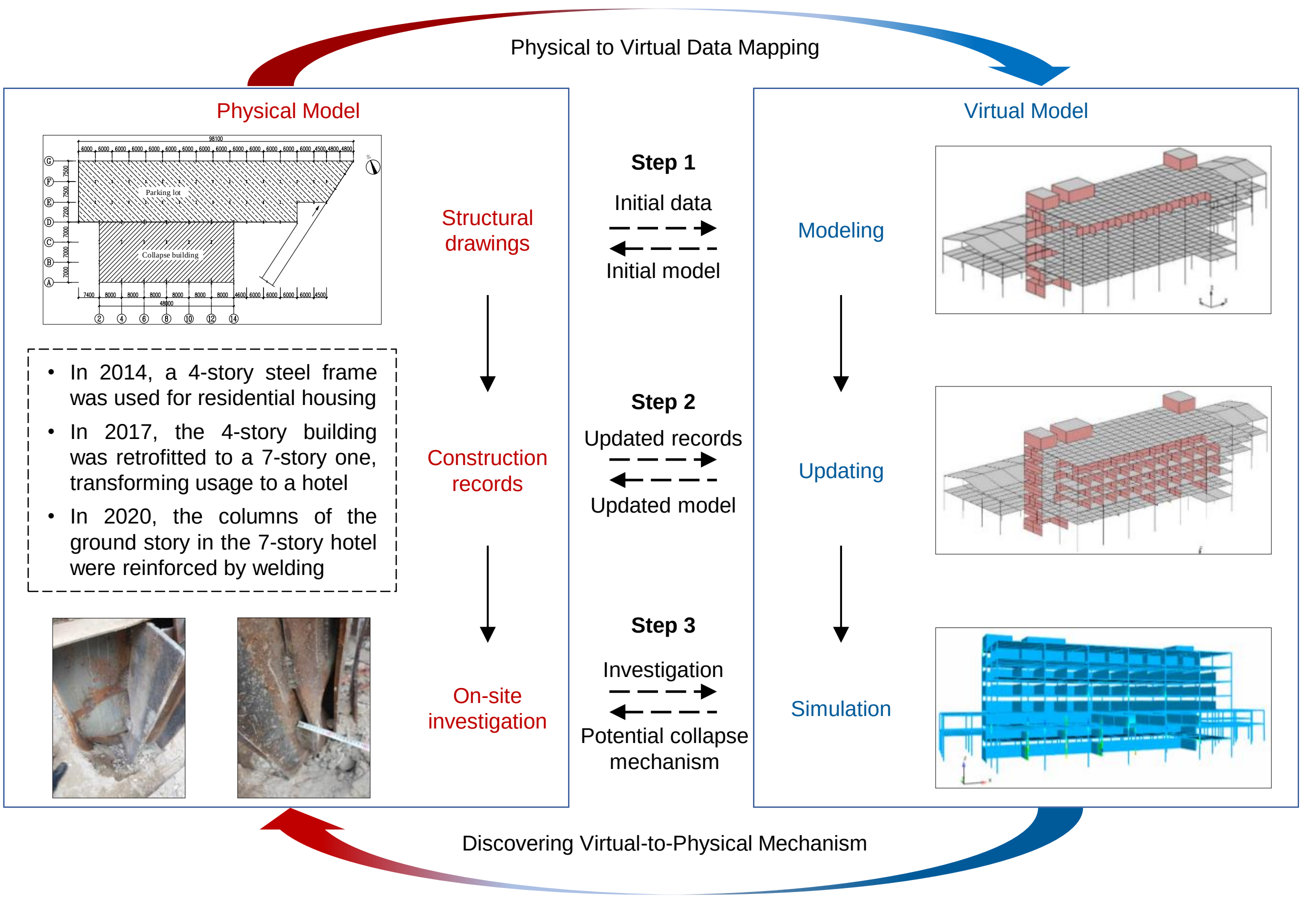


Figure 1. Architecture of the proposed digital twin-based collapse investigation method

Step 1: Data collection and modeling. First, necessary information, such as architectural, structural, and construction drawing details of the building, should be collected from the physical model. Then, the virtual models, including the BIMs and FEMs of the building, are established based on the collected information. In this stage, information flows from the physical model to the virtual model.

Step 2: Construction and updating. On the one hand, the virtual models are constantly updated as more building information is collected from the physical model. For example, when the construction and renovation information of a building is available, virtual models can simulate the renovation and construction process based on the information. On the other hand, some mechanisms may be revealed by simulating virtual models, which can better guide the information search process in the real world. In other words, the virtual model provided decision support to the physical world. For example, a column approaching instability can be identified via virtual model analysis, indicating that column failure is likely to cause building collapse. Therefore, more attention should be paid to the column of the building during the search process in the physical model. In this stage, information is iteratively exchanged between the physical and virtual models.

Step 3 On-site investigation and simulation. After collecting sufficient data from the physical model, the virtual model is utilized to reproduce building collapse and reveal the underlying causes. Finally, the debris from the collapsed building simulated from the virtual model is compared with real debris, which validates the collapse mechanism determined from the virtual model analysis. In this stage, information flows from the virtual model to the physical model.

Moreover, a real building collapse accident was utilized to illustrate the proposed method. Accordingly, the details of Steps 1–3 are shown in Sections 3–5, respectively. Finally, Section 6 concludes the study.

3. Digital twin of the building

3.1 Collapse accident of a building

The adopted case is the collapse accident of a seven-story building (Figure 2(a)). The building collapsed after welding strengthening in 2020, and the debris is shown in Figure 2(b). The collapsed building was initially a conventional steel frame structure. However, the building underwent many functional changes over the years, and its structure changed correspondingly. Therefore, the complex retrofitting process and irregular internal structure led to complicated loading states and collapse accidents. The complex retrofitting process also makes it difficult to reveal the potential collapse mechanism using conventional analysis methods. The digital twin-based collapse investigation method can provide a comprehensive and accurate understanding of the building at each stage from construction to collapse. Therefore, to establish the digital twin model, we collected the necessary information about the building from construction to collapse. Based on this information, we established the corresponding digital twin models (see Section 3) and updated the models several times from the initial state to the critical state before collapse (see Section 4).

Figure 2. Hotel building before and after the collapse. (a) The hotel building before collapse (the hotel name is anonymous). (b) Ruin after the collapse.

3.2 Building information and data acquirement

The building was retrofitted many times, and the major retrofitting processes are briefly presented in Figure 3. In the first stage, the building was a four-story commercial building, and the building was safe. In the second stage, the building underwent major retrofitting. Subsequently, the building was remodeled into a seven-story hotel. In the third stage, welding strengthening was applied to the base columns of the building. Subsequently, the building collapsed.

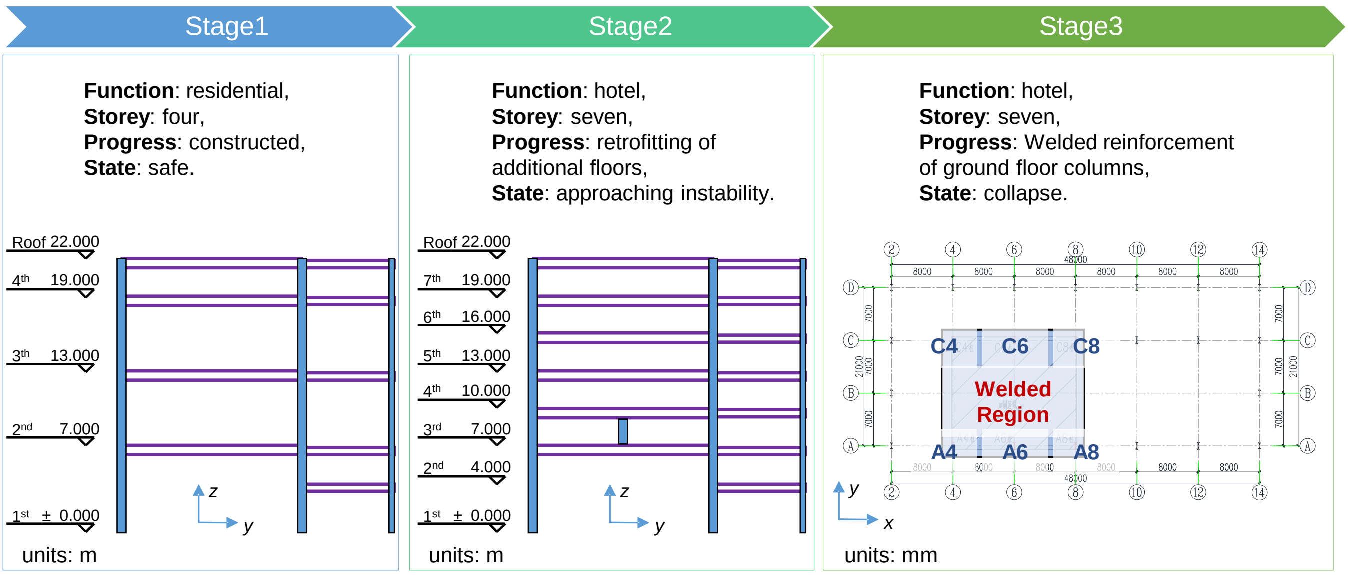


Figure 3. Conversion of the building

The plane view and elevation view of the building in Stage 2 are shown in Figure 4. The height of the collapsed building is 22 m. The length of the building in the east–west direction is 48 m, with 8 m × 6 spans, and the length of the building in the north–south direction is 21 m, with 7 m × 3 spans.

The building is a steel frame structure, and the primary components, that is, the column, beam, infill wall, and floor, should be created in the virtual models. The beams and columns were all equipped with H-shaped cross-sections, and their material strengths were determined according to the on-site test results. The yield strength F_y of the steel columns was 336 MPa, and the yield strength F_y of the steel beams was 313 MPa. The elastic modulus, E_s, of the steel beams and steel columns was 205 GPa. A detailed steel column layout drawing of the typical floors of the building is shown in Figure 5(a). A detailed steel beam layout drawing of the typical floors is shown in Figure 5(b). In terms of the infill walls, the strength grade of the bricks in the building infill wall was MU10. The standard value of compressive strength according to the *Code for Design of Masonry Structures* [25] is 1.48 MPa, and the elastic modulus is 1.165 GPa. The strength grade of the concrete in the slab is C20. The standard value of compressive strength according to the *Code for Design of Concrete Structure* [26] is 13.4 MPa, and the elastic modulus is 25.5 GPa. Furthermore, the on-site investigation revealed that the thickness of the structural floor used in the virtual models was 130 mm.

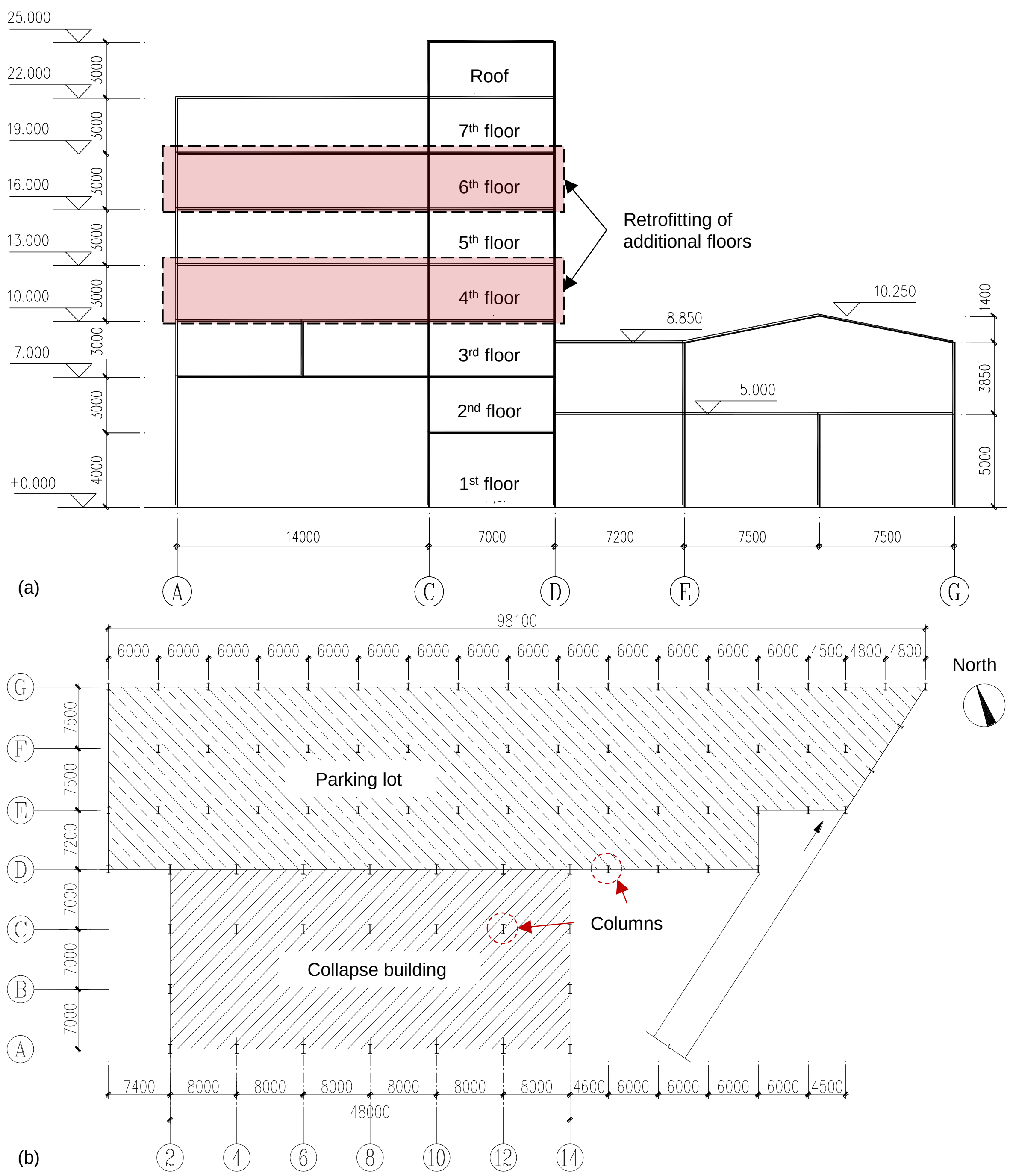
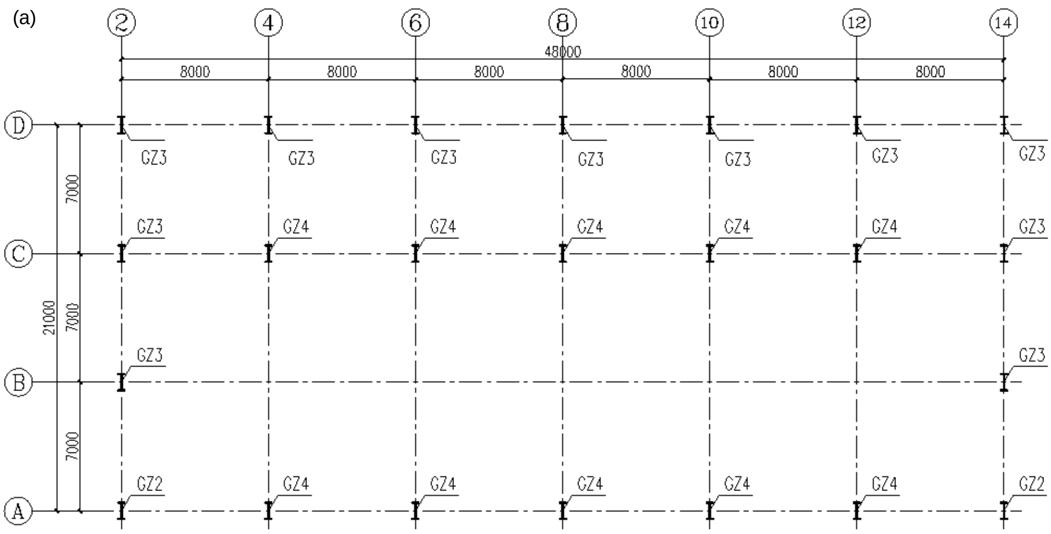
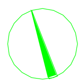


Figure 4. Basic views of the building (a) Elevation view (the elevation units: m; other units: mm). (b) Plane view (units: mm).

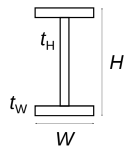
(a)



North



Name	$H{\times}W{\times}t_H{\times}t_W$ (mm)	Name	$H{\times}W{\times}t_H{\times}t_W$ (mm)
GZ 1	396×199×7×11	GZ 3	446×199×8×12
GZ 2	496×199×9×14	CZ 4	596×199×10×15



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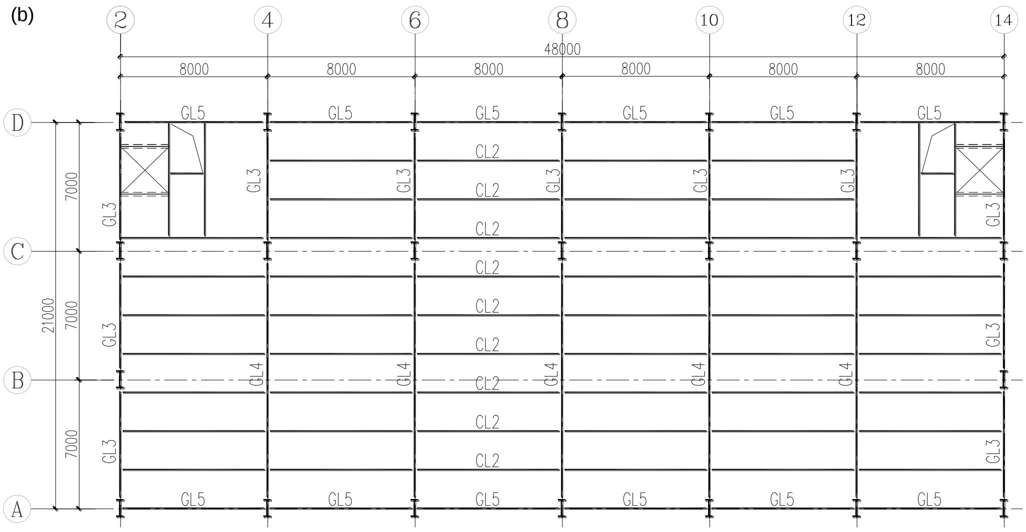
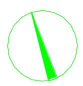
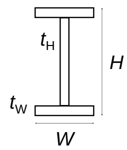


North



Name	$H{\times}W{\times}t_H{\times}t_W$ (mm)	Name	$H{\times}W{\times}t_H{\times}t_W$ (mm)
GL 3	(634~396)×199×7×11	GL 5	346×174×6×9
GL 4	(1200~800)×299×10×14	CL 2	346×174×6×9



(c)

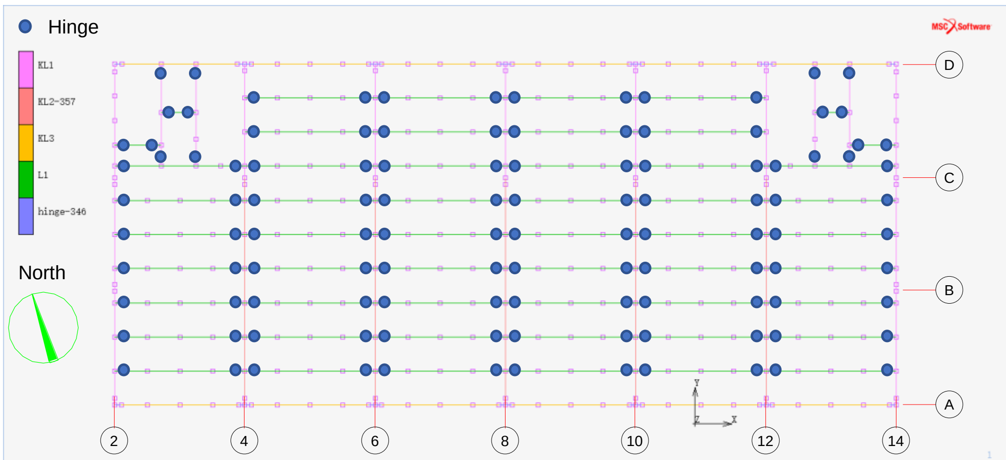


Figure 5. Drawings of the typical floor. (a) Column layout (units: mm). (b) Beam layout (units: mm). (c) Connections between beam and columns.

After additional floors were retrofitted, the building transitioned from Stage 1 to Stage 2. The floors and infill walls were added to the structure, and the floor load was changed. In this study, the floor load values of the structure of all stages were calculated based on detailed structural information, including the decoration of floor slab and infill walls, self-weight of slabs, infill walls, ceilings, and glass curtain walls. The floor load values are listed in Table 1.

Table 1. Floor load of the building

Floor number	Load of Stage1		Floor number	Load of Stage2&3	
	Dead load (kN/m^2)	Live load (kN/m^2)		Dead load (kN/m^2)	Dead load (kN/m^2)
2^{nd}	3.35	1.00	2^{nd}	3.35	0.01
3^{th}	4.60	0.00	3^{th}	5.30	0.01
4^{th}	4.30	0.00	4^{th}	4.05	0.05
5^{th}	5.30	1.00	5^{th}	4.80	0.05
Roof	4.10	0.00	6^{th}	4.43	0.05
			7^{th}	4.80	0.02
			Roof	4.10	0.00

*Note that we collected detailed structural component dimensions, structural layout drawings, and material information from the building. Owing to copyright, only the most relevant information is presented in this paper.

3.3 Digital twin model development

After collecting the data from the physical model, the BIM of the building in Stage 1 was established using Revit [27] for effective data integration, as shown in Figure 6. BIM can effectively integrate the relevant information and data (e.g., the location of the infill walls, detailed cross-section of beams and columns, and material information) from the physical model. Therefore, BIM is the basis of subsequent FEMs and physics engine models.

Subsequently, based on the detailed information provided by the BIM, a 3D FEM of the overall structure in Stage 1 was established using MSC.Marc [28]. Various types of elements are used to simulate different building components, considering their compatibility. The beams and columns were modeled with fiber beam elements considering the local buckling effect [29]. The infill brick walls were modeled using shell elements. The slabs were modeled using membrane elements. The adopted modeling methods have been widely used in previous studies [29-31]. The cross-sectional dimensions and structural layout are shown in Figures 4 and 5, respectively. The beams along the A-axis direction were primarily hinged and connected to the corresponding columns. Therefore, the rbe2 element [28] was used to model the hinged connection, releasing the rotational degree-of-freedom. Meanwhile, the beams along the 2-axis are rigidly connected to the corresponding columns. The typical connections between the beams and columns are shown in Figure 5(c). The steel columns of the base floor were rigidly connected to the ground. The above-mentioned building modifications are illustrated in Section 4.

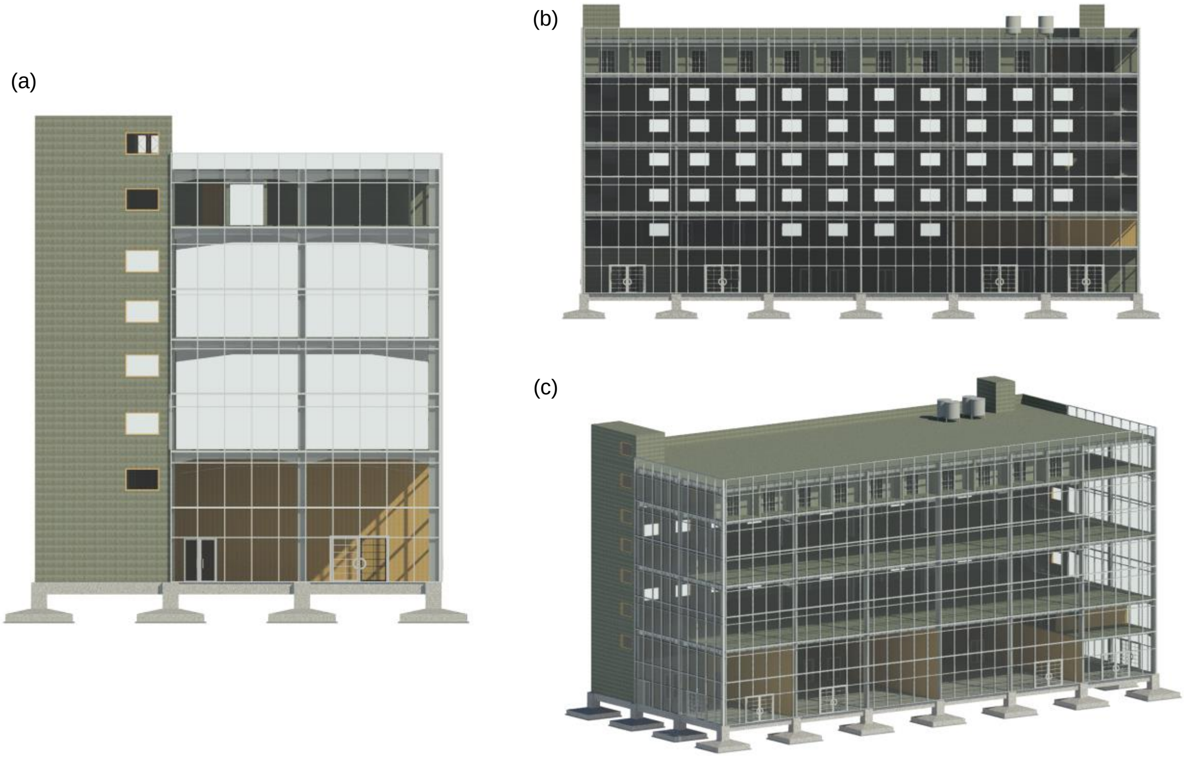


Figure 6. BIM of the building in Stage 1. (a) Left side view. (b) Front view. (c) Axonometric view.

4. Digital twin model updating

4.1 Model updating of BIM based on construction log

From the information collected from the construction logs, the key processes for the major retrofitting of additional stories are as follows.

Step 1: Steel column construction on the third floor (7–10 m);

Step 2: Steel beams and floor slab construction of the fourth floor (10 m); interior wall construction on the third floor;

Step 3: Interior wall construction on the fourth floor;

Step 4: Interior wall construction on the fifth floor;

Step 5: Reinforced concrete floor slab construction on the sixth floor (16 m).

Step 6: Interior wall construction on the sixth floor;

Step 7: Elevator installation and elevator machine room construction on the roof;

Step 8: Window and door installation, and water tank installation on the roof;

Step 9: Covering the steel columns of the first floor with 800 × 800 mm wooden boards and covering the steel columns on the D-axis with ceramic tiles.

The BIM is then updated based on construction log information. The BIM before the update (i.e., Stage 1) is shown in Figure 7(a), and the updated BIM is shown in Figure 7(b). An animation of the construction process was created to demonstrate the major retrofitting of additional stories. Specifically, the Revit model is first exported as a Filmbox (FBX) file [32], and the FBX file is then imported into Twinmotion [33]. The construction process is then simulated. Continuous screenshots of the construction process are presented in Figure 8.

The intuitive and visual nature of BIM also provided a useful aid to understanding the layout and retrofitting process. The powerful visualization display ensures smooth communication and close cooperation among the multidisciplinary professionals on the investigation team. The digital twin-based method can better quantify the uncertainty of the virtual models. There are lots of uncertainties in the modeling process. If only simulation-based methods are used, the result of collapse analysis relies fully on quantifying uncertainties in building modeling [12]. If there was a discrepancy, the simulation result and the real world could be quite different. Thus, via utilizing the digital twin-based method, the BIM model of the digital twin model enables the domain experts in the physical world to carefully confirm and correct the virtual model to quantify and then reduce the uncertainties. An accurate digital model can provide critical support for the determination of structural loads and construction methods. This assists research and analysis to determine the causal factors of accidents.

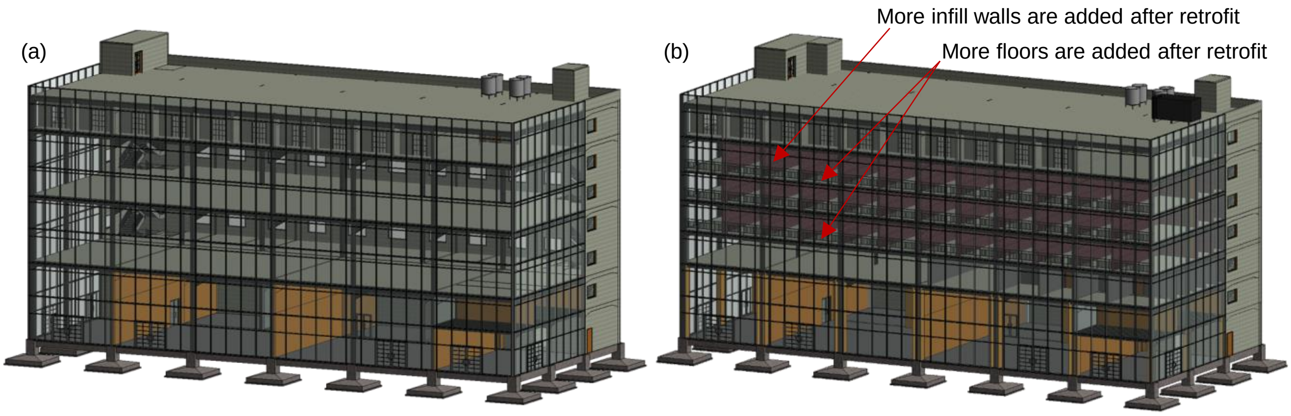


Figure 7. Updating the BIM. (a) Original model. (b) Updated model

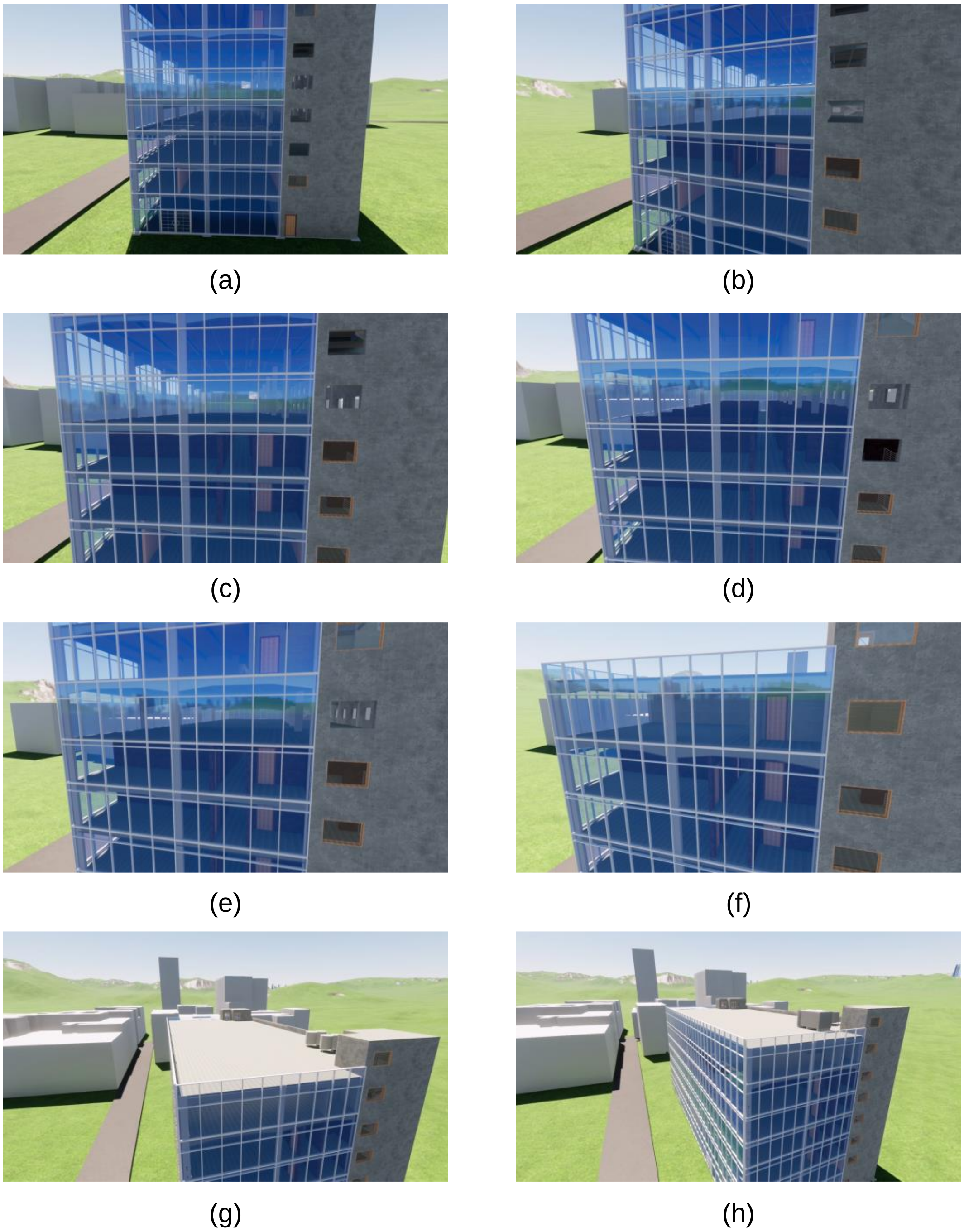


Figure 8. Updating the BIM animation. (a)–(h) Steps 1–8.

4.2 Finite element model updating and analysis

Depending on the changes in the building structure and load determined by the BIM, the FEM is updated. The modeling method for FEMs based on MSC.MARC [28] is described in Section 3.2. To investigate the real-world state of the building, the actual loads are applied (i.e., 1.0 dead load + 1.0 live load). In addition, the pushdown method [31, 34, 35] was used to evaluate the vertical load safety redundancy of the structure in each phase. In the FEM, the pushdown method can be utilized by increasing the vertical load (i.e., simultaneously increasing the dead load and live load) until the structure collapses. The vertical load safety redundancy was obtained by dividing the collapse load by the current vertical load.

(1) Stage 1. The initial structure before retrofitting is four stories. The analysis results show that the total gravity load of the model before retrofitting was 3114 tons. The vertical ultimate bearing capacity of the structure calculated by finite element analysis was 5208 tons. Therefore, the total weight accounts for approximately 60% of the vertical ultimate bearing capacity. The maximum axial force of the first-story column was approximately 232 tons (C4), which was 63% of its stable ultimate bearing capacity. Therefore, the structure was in an elastic state.

(2) Stage 2. The structure after the major retrofit had seven stories. The analysis results showed that the total gravity load of the modified model was 5214 tons, and the vertical load increased by 67%. The analysis results showed that the vertical ultimate bearing capacity of the structure was 5312 tons. Therefore, the total weight accounts for approximately 98% of the vertical ultimate bearing capacity and exceeds the vertical ultimate bearing capacity of the original four-story structure of 5208 tons. The maximum axial force of the first-story column is approximately 389 tons (C8), which is 105% of the theoretical ultimate load-carrying capacity of the column on the C axis. The maximum compressive stresses in the web plates of steel columns C6, C8, and C10 in the structure exceeded their buckling stress. The structure was in a critical state.

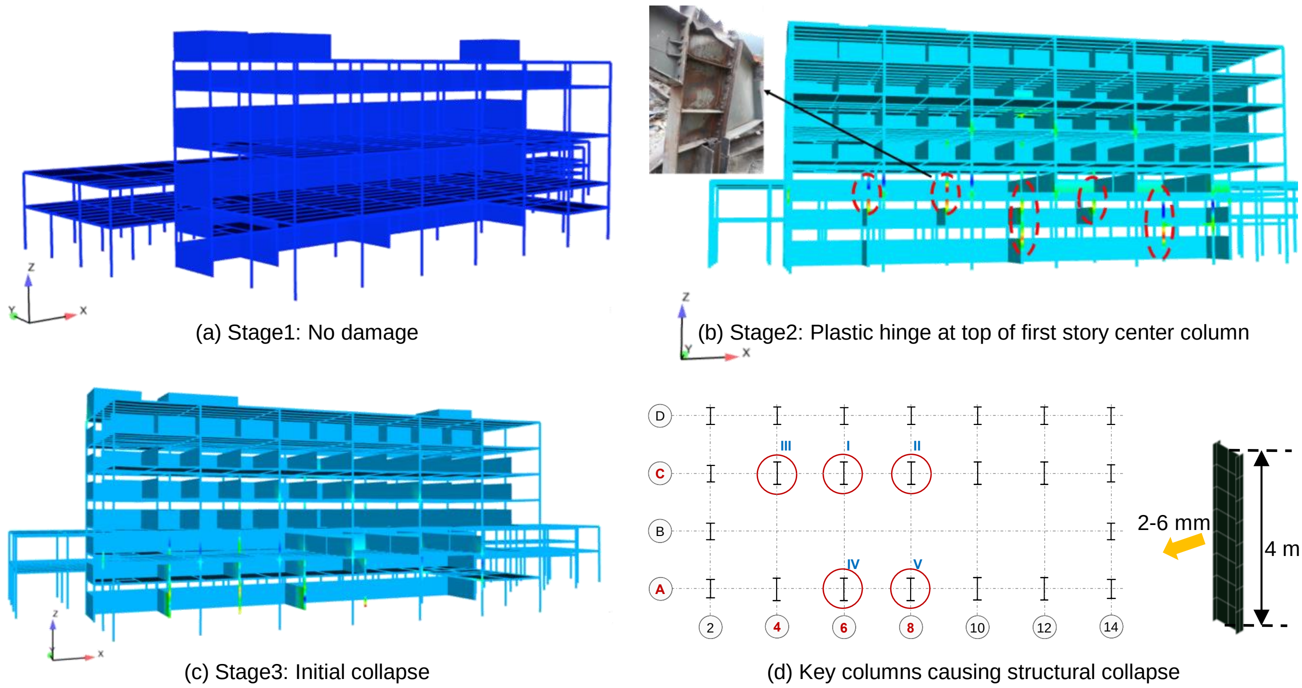


Figure 9. Axial forces of the beams and columns of the building. (a) Stage 1. (b) Stage 2. (c) Stage 3. (d) Critical elements

(3) Stage 3. After the welding strengthening in Stage 3, the building collapsed. According to the analysis results of the FEM of Stage 2, the total structural gravity load of the retrofitted 7-story steel structure under the actual use load is 5214 tons, which is very close to the vertical ultimate bearing capacity. Although the bottom columns were in a critical state and plastic deformation occurred, the structure did not collapse. This suggests that the immediate cause of building collapse requires further investigation.

According to the BIM construction process, the structure collapsed after welding strengthening on the partial columns on the ground story. Therefore, the results of the analysis of the digital twin model indicate that the effects of welding need to be considered. The research team then conducted an on-site investigation. According to the on-site investigation results, in this welding construction, the lower section of the steel columns (e.g., C4, C6, and C8) at the bottom introduced a horizontal deformation with an amplitude of 2–6 mm. Thus, according to the on-site investigation results, the corresponding horizontal deformation was added to the FEM based on the analysis of Stage 2. Subsequently, the structure underwent initial collapse.

5. Collapse analysis using the digital twin model

5.1 Analysis of the collapse mechanism

According to the on-site investigation results, horizontal deformation of 2–6 mm occurred at Stage 3. In the subsequent simulation, the structural plastic deformation and damage rapidly and disproportionately propagated, and the structure entered the collapsed state, as shown in Figure 10.

Therefore, according to the finite element analysis results, the local buckling, plastic deformation, and flexural deformation of the bottom columns are increased by the welding construction. Taking the bottom C4 steel column as an example, the horizontal deformation in the middle increases by 2–4 mm. As a result, severe disturbances were generated owing to the high load, inducing damage to the bottom steel columns and the overall collapse of the structure. Thus, the mechanism and critical causes of the structural collapse accident were determined.

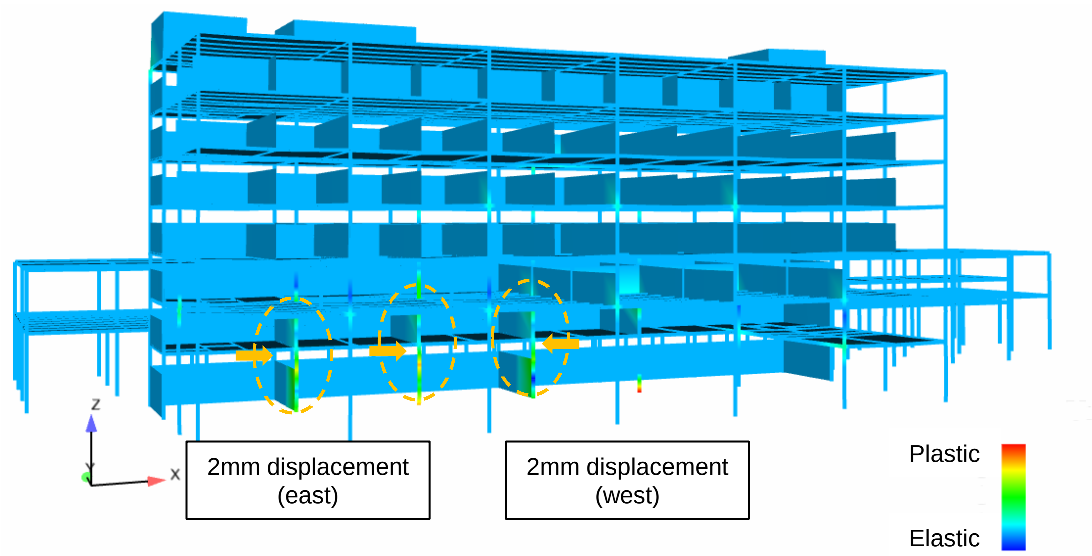


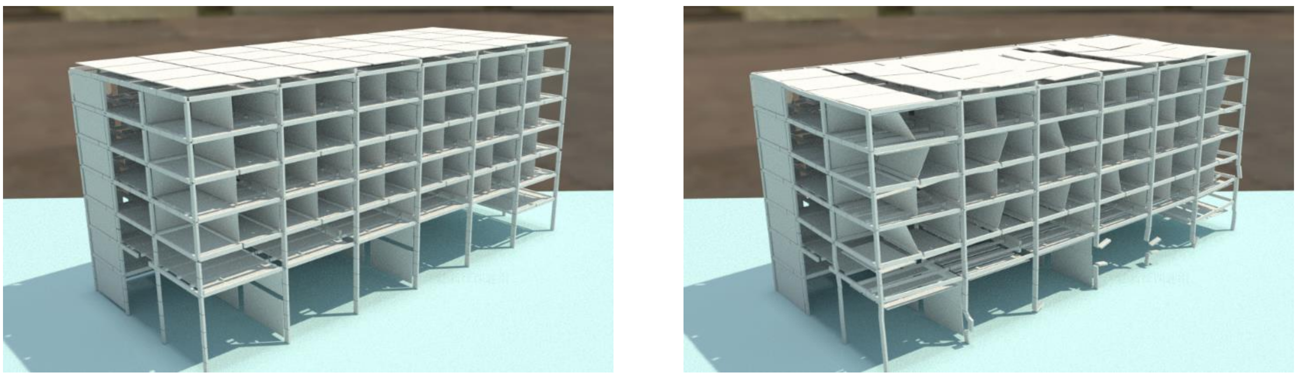
Figure 10. Collapse initial state of the building

5.2 Visualization of the collapse progress

To validate the building collapse mechanism via the virtual model analysis, a collapse visualization analysis was conducted using the collapse simulation technique based on the physics engine [4, 36, 37]. Subsequently, the simulated virtual wreckages were compared with the actual physical collapse wreckages at the site. The collapse visualization method proposed by Lu et al. [4] was adopted. The simulation is implemented in three primary steps: (1) geometric model establishment and conversion, (2) establishment of physics engine model, and (3) introduction of initial damage [4]. First, the FEM in the virtual model of the digital twin was utilized as the geometric model. Then, the geometric model was converted into a physics engine model using tools developed by Zheng et al. [36]. Subsequently, the initial disturbances are applied to the C4, C6, and C8 columns welded at the bottom of the physics engine model based on the causes of collapse identified in Section 5.1. Finally, the collapse processes were simulated using the physics engine model, and the simulated collapse processes of the building are shown in Figure 11.

Initially, the middle steel column of the first floor on the A-axis bends in the east–west direction (Figure 11(b)). The vertical compressive bearing capacity of the steel column decreased rapidly, resulting in the steel column being unable to support the gravity weight of the upper structure. Subsequently, the upper structures, especially the parts of the three stories above the range from axis A to axis C, start to collapse. Meanwhile, the buildings started to tilt in the southern direction (Figure 11(c)). The span of the building along the C-axis to D-axis direction is 7 m, which is shorter than the span along the A-axis to the C-axis direction of 14 m. Moreover, there are more infill walls in the north–south direction along the C-axis to the D-axis than along the A-axis to the C-axis. The column at the A-axis gradually loses its load-carrying capacity, and the load from the upper structure is then transferred to the columns at the C-axis and D-axis. This resulted in severe buckling of the column at the C-axis and accelerated the overall collapse of the upper structure. Subsequently, the third-floor slab near the A-axis first touched the ground (Figure 11(d)). Gradually, as the overall southward tilt deformation increased, the upper floors successively came to the ground. The column at the D-axis was subjected to increasing tension, and the bottom of the column was pulled off (Figure 11(f)). After that, the whole building fell toward the south, and the floor slab broke apart. Finally, the collapse process was completed, and only debris was left.

The simulated debris distribution of the building is shown in Figure 12; on the left are stills from the photos taken from the building site, and the right subfigures are the simulated results. Figure 12 shows that the simulated debris distribution agrees well with the actual collapse wreckage, indicating that the proposed collapse investigation method realistically reproduces the building collapse process.



(a) (b)

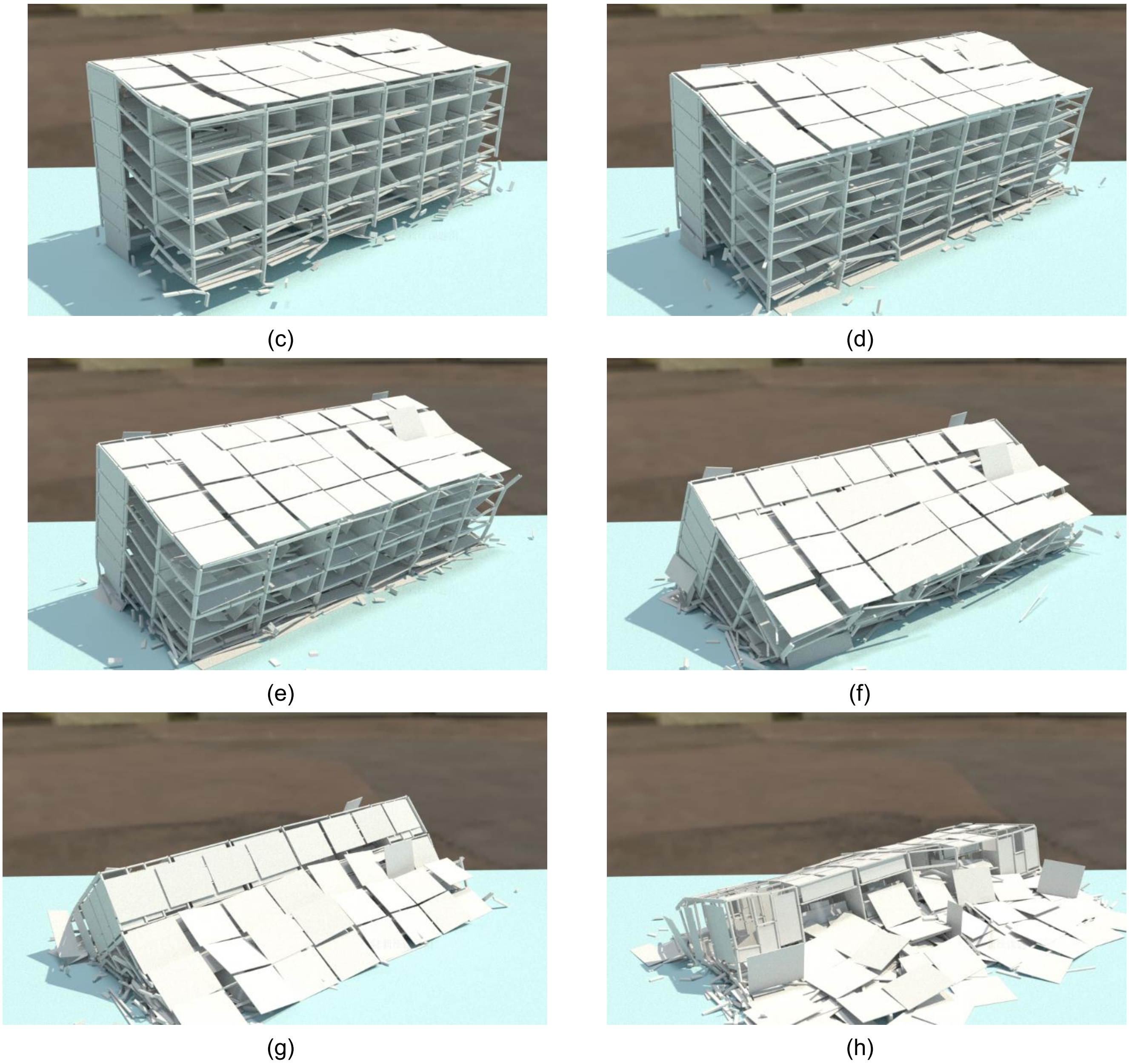


Figure 11. Collapse progress of the building (a) Collapse begins; (b) Column at A-axis starts buckling; (c) The columns on the first floor at the A-axis lose their vertical bearing capacity; (d) The third-floor slab at A-axis first touch the ground, and the upper structure tilted to the south; (e) The fourth-floor slab first touch the ground, and the upper structure is severely tilted; (f) Column at D-axis pull off, and several floors at A-axis touch the ground; (g) The building tipped to the south and several upper floors touched the ground; (h) Collapse process complete

Figure 12. Comparison between actual physical collapse wreckages and simulated virtual wreckages (a) Actual collapse scenario (side view); (b) Simulated collapse scenario (side view); (c) Actual collapse scenario (front view); (d) Simulated collapse scenario (front view); (e) Actual collapse scenario (top view); (f) Simulated collapse scenario (top view)

5.3 Interaction in virtual and real spaces to reveal the accident mechanism

The above analysis validates the effectiveness of the proposed digital twin-based collapse analysis method. The method can reproduce the collapse process in the virtual space and, thus, assists in investigating the causes of collapse accidents. In addition, the proposed digital twin-based collapse analysis method also reveals that defects or damage in the critical areas of buildings are important factors causing building collapse, which implies that the critical regions should be identified as soon as possible. In practice, proper strengthening and monitoring of these critical regions can effectively prevent building collapse.

Digital twin-based methods can better assist decision-making in the physical world. Collapse accident sites are dilapidated and chaotic, making it difficult to determine the cause of the collapse only using site investigation-based methods. On the one hand, the site investigation found local buckling of the ground floor columns. Therefore, the traditional methods may regard the local buckling as the cause of the collapse. However, the digital twin-based method pointed out that the local buckling was caused by the gravity load in Stage 2, which helps the investigation avoid being misled by the local buckling on-site and supports making a reasonable decision. On the other hand, the digital twin-based method pointed out that welding was the direct cause of the building collapse. The welding leads to an increase in the internal force of the component, which in turn causes the overall horizontal deformation of the component, and then eventually leads to the collapse of the whole structure. The simulation results of the collapse mode are consistent with what happened in the physical world, which provides effective support for the accident investigation.

The analysis results in this work also provide practical strategies for future disaster prevention and control, such as strict investigation of structural retrofits, increasing the structural health monitoring technology, and developing a digital twin for disaster evolution.

6. Conclusions

Collapse accident sites are dilapidated and chaotic, making it difficult to determine the cause of collapse using traditional methods. Therefore, to improve the accident investigation, a digital twin-based accident investigation framework is proposed to conduct the investigation. The digital twin-based framework consists of the physical objects (e.g., structural drawings, construction records, and site investigation), the virtual model (e.g., BIM model, FE model, and physics engine model), and the interaction between the physical and virtual spaces. A real collapse accident and corresponding on-site investigation results were used to validate the proposed method. The results indicate that the digital twin-based method supports the decision-making process and the determination of real causes. Via the information interaction between the physical world and the virtual world, the real cause of the accident can be revealed more reliably. The major findings are summarized below.

(1) In the building collapse case, the maximum compressive stress in the columns on the ground floor of the building exceeded its critical buckling stress. The welding construction process led to local buckling and plastic deformation of the ground floor columns, which further resulted in large flexural deformation in the columns. This caused severe disturbance to the highly loaded steel columns, which induced damage to the columns on the ground floor and the overall collapse of the structure.

(2) With improvements in FEM, BIM, physics engine, and model updating techniques, the digital twin technology can be used for the collapse scenario simulation and cause investigation of structural collapse accidents.

Even if the service history of the engineering structure is complex, the digital twin model can effectively record and update the series of changes, which can assist in the analysis of complex collapse mechanisms.

(3) The case study also demonstrates that the digital twin model has great potential for engineering disaster prevention and control. The digital twin model can provide effective data and platform support for performance evaluation and health monitoring of the structure.

This work is a preliminary exploration of digital twin-based accident investigations. The decision-making process is supported by digital twins, which helps to find the actual cause of the collapse accident. But the accident has already occurred and caused heavy losses. In future research, digital twin-based models are encouraged to be established for important buildings in advance to perform multi-hazard simulation analysis. In this way, the mechanical state of the key components of the building can be monitored all the time, thereby avoiding disasters.

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Competing interests

The authors declare no competing interests.

Data availability statement

All inquiries regarding this content should be directed to the corresponding author.

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