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EERI Earthquake Reconnaissance Report:

M_L 7.2 Earthquake of April 3, 2024 in Hualien, Taiwan

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PREFACE

An earthquake with an epicenter at Shoufeng Township, Hualien County, eastern Taiwan occurred in the morning on April 3, 2024. The Richter magnitude (M_L) of the earthquake was 7.2, and the seismic intensity reached level 6+, the second highest on Taiwan's intensity scale. This event stands as the strongest earthquake in Taiwan since the 1999 Chi-Chi earthquake (M_L 7.3). It was accompanied by four aftershocks exceeding M_L 6.0 in April. The earthquake resulted in at least 18 fatalities and over 1,100 injuries. Soon after the seismic event, Taiwan's National Center for Research on Earthquake Engineering (NCREE) and the Mexican Society of Earthquake Engineering (SMIS) conducted an international collaborative reconnaissance for filed inspection of buildings in the most affected areas including Hualien County, Taipei City, Taipei County, and Taoyuan City.

The main earthquake caused major damage in Hualien County, including the collapse of two buildings and severe damage to several others. This report presents and discusses the damaged and undamaged buildings observed during the post-earthquake inspection. The undamaged buildings include five buildings retrofitted before the earthquake event and two base-isolated buildings. Moreover, to explore why the seismic loss from the earthquake event is significantly minor in comparison with that from the 1999 Chi-Chi earthquake, the measures taken in Taiwan for seismic preparedness during the 25 years following the 1999 Chi-Chi earthquake are addressed. The report aims to share the knowledge gained and highlight relevant aspects that could enhance the performance of buildings under future seismic events. Thus, some inspected buildings were selected and categorized into damaged and undamaged buildings for further discussion. It should be noted that some of the illustrations and discussion on the inspected buildings in Hualien County have been submitted to a journal and is currently under review. Through the international collaborative filed inspection, the conclusions drawn in this report are preliminary, and further analysis of the collected data will provide deeper insights and more definitive conclusions regarding the seismic reconnaissance.

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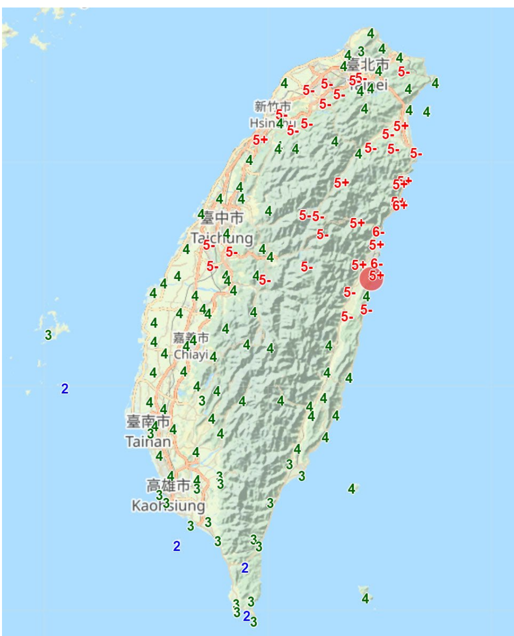
1 INTRODUCTION

Taiwan is in the world's most seismically active zone, Circum-Pacific earthquake belt also known as the Ring of Fire. Because of the tectonically complex region, Taiwan has historically experienced many large earthquakes with magnitudes of 7 or higher. An earthquake with an epicenter at Shoufeng Township, Hualien County in eastern Taiwan occurred on the morning of April 3, 2024. The Richter magnitude (M_L) of the earthquake measured by Taiwan's Central Weather Administration (CWA) was 7.2 (CWA, 2024). Figure 1 shows the CWA's report on the M_L 7.2 seismic event, referred to as the 0403 Hualien earthquake hereafter. The maximum seismic intensity was 6+, which is the second-strongest ground motion intensity level in Taiwan (CWA, 2023). This event marks the strongest earthquake in Taiwan since the 1999 Chi-Chi earthquake (M_L 7.3) (Christopoulos et al., 2005; Lin et al., 2022) that resulted in at least 2,444 victims (2,415 deaths and 29 missing people), 38,935 collapsed buildings, and US$12 billion in financial losses. The CWA recorded 1,416 aftershocks by 11:02 AM on May 9, 2024, including four events exceeding a magnitude of M_L 6.0. The highest intensity level measured from the aftershocks was 5+. There were at least 18 deaths and over 1,100 people were injured because of the 0403 Hualien earthquake. The main seismic damage included two collapsed buildings with soft bottom stories. The collapse of the two buildings due to the major earthquake did not cause any fatalities, but only one person was killed by an aftershock when the victim returned to one of the two collapsed buildings. Most fatalities and injuries occurred because of landslides and rockfalls in Taroko National Park, Hualien County.



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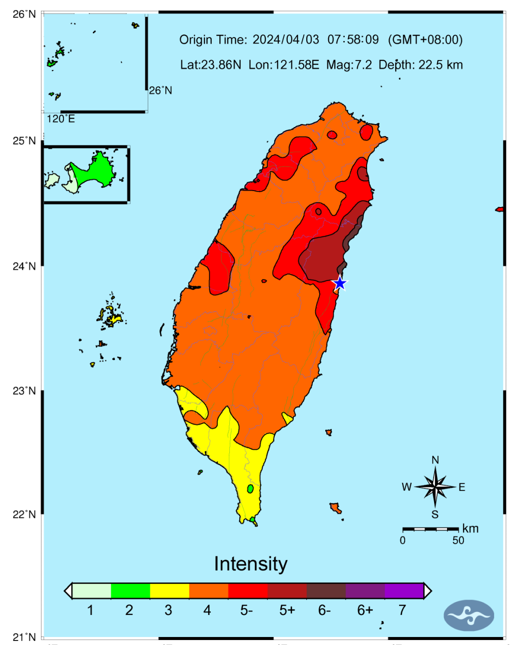

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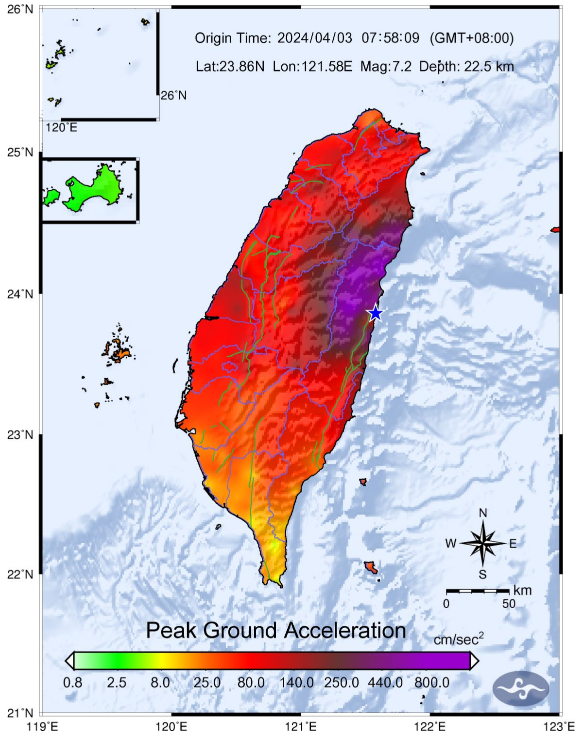

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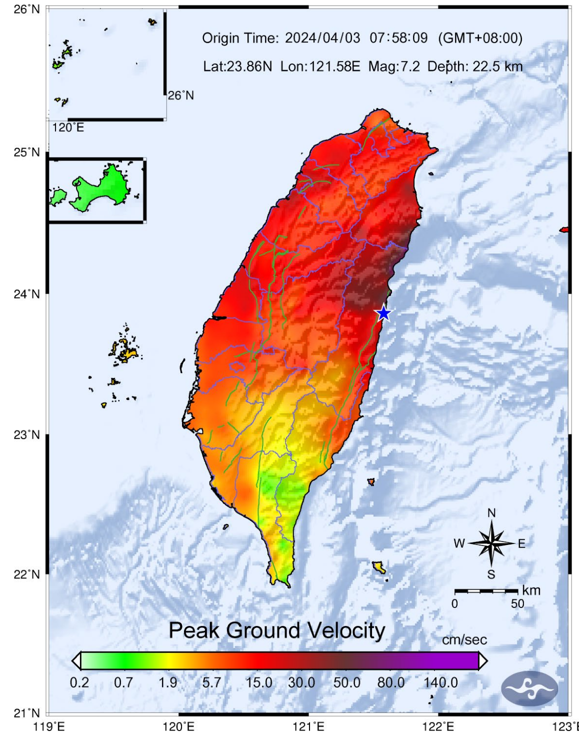

(d)

Figure 1. CWA's maps of (a) distribution of strong motion stations with reported intensity levels, (b) seismic intensity, (c) PGA, and (d) PGV of the 0403 Hualien earthquake.

According to the guidelines for rapid post-earthquake building assessment of Taiwan's National Land Management Agency, Ministry of the Interior, red placards indicate buildings with damage to main structural elements or buildings with unstable foundations. Yellow placards denote buildings with damage to non-structural elements that may collapse or buildings that may be damaged by surrounding impaired buildings. After the 0403 Hualien earthquake and numerous aftershocks, many damaged or hazardous buildings in Taipei City, New Taipei City, Taoyuan City, and Hualien County were reported. Most red-tagged or yellow-tagged buildings were concentrated in Hualien County, nearest to the epicenter of the earthquake. By June 5, 2024, the count of red-tagged and yellow-tagged buildings in the Hualien area was 90 and 89, respectively.

Soon after the seismic event, Taiwan's National Center for Research on Earthquake Engineering (NCREE) sent two reconnaissance teams from the Building Engineering Division to investigate earthquake impacts on the damaged buildings across Taiwan. The first team surveyed damaged buildings in Hualien City/County from April 6 to April 8. The second team conducted inspections in Taipei City, Taipei County, and Taoyuan City on April 9. The inspected buildings of the second reconnaissance team are located in seven areas, included a mixed-use building complex in Nanjichang Night Market in Taipei City, Zhonghe Senior High School in New Taipei City, three street buildings in Tucheng District of New Taipei City, a traditional market in Daxi District of Taoyuan City, and a residential building in Zhongli District of Taoyuan City. Figure 2 shows the locations of the inspected buildings in the aforementioned areas. The conclusions drawn in this report are preliminary, and further analysis of the collected data will provide deeper insights and more definitive conclusions regarding the seismic reconnaissance.

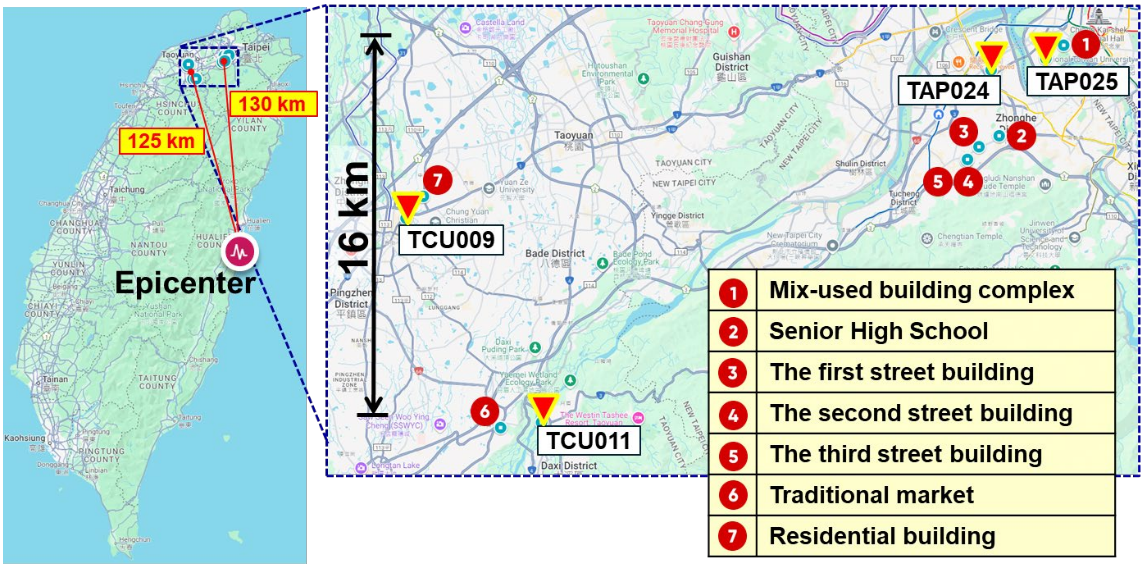

Figure 2. Locations of inspected buildings in Taipei City, New Taipei City, and Taoyuan City (credit: Google Maps).

Three weeks after the seismic event, NCREE and the Mexican Society of Earthquake Engineering (SMIS) teamed up to conduct detailed post-earthquake inspections in the worst-affected areas (Figure 3), in collaboration with scholars and professional engineers from Taiwan and Canada. Seismic reconnaissance focused not only on damaged or collapsed buildings but also on undamaged buildings, which were seismic retrofitted before the 0403 Hualien earthquake.

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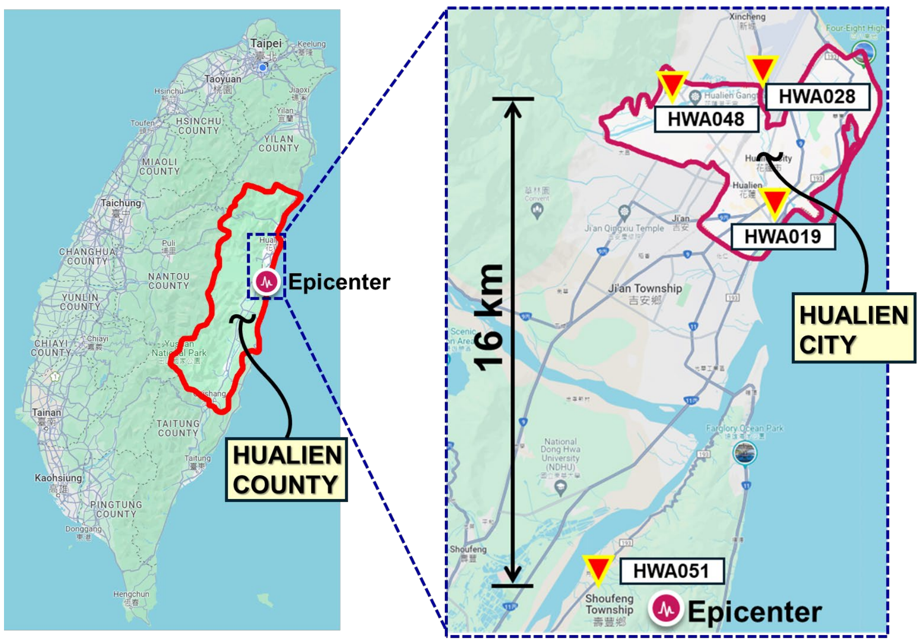


(a) (b)

Figure 3. Maps of (a) epicenter of the 0403 Hualien earthquake, and (b) selected strong ground motion stations in Hualien County (credit: Google Maps).

This study explores the issues and challenges relating to learning from the 0403 Hualien earthquake that might improve design practices in earthquake-prone areas. For the brevity, the authors presented the selected damaged buildings and iconic retrofitted buildings located in Taipei City, Taipei County, Taoyuan City, and Hualien County for sharing the knowledge gained to provide insight into the seismic performance of buildings subjected to the 0403 Hualien earthquake.

2 GROUND MOTION CHARACTERISTICS

2.1 Overview

The 0403 Hualien earthquake with a magnitude of M_L 7.2 occurred at 7:58:09 local time (UTC+8) on April 3, 2024. The epicenter was in Shoufeng Township, Hualien County, at coordinates 23.86°N, 121.58°E, approximately 14.9 km in the SSW direction from the Hall of Hualien County Government. The depth of the hypocenter was 22.5 km. The seismic intensities were reported as 6+ in Heping, Xiulin Township of Hualien County, 6- in Hualien City and Taroko, and 5- in Taipei City and New Taipei City. Figure 1 shows the distributions of strong motion stations and the CWA-measured seismic intensities, peak ground accelerations (PGAs), and peak ground velocities (PGVs) (CWA, 2024). The earthquake had a focal mechanism corresponding to reverse-faulting near the boundary between the Eurasian and Philippine Sea Plates (USGS, 2024).

2.2 Characteristics of near-fault ground motions

Pulse-like velocities were observed at three strong ground motion stations by using the Taiwan Rapid Earthquake Information Release System (NCREE, 2024). These strong-velocity pulses were identified using the pulse indicator proposed by Shahi and Baker (2014). The corresponding pulse periods of the stations ranged from 3.4 s to 3.7 s. Additionally, eleven pulse-like velocity time histories were recorded at stations within the Taiwan Strong Motion Instrumentation Program (TSMIP) network. Nevertheless, pulse-like velocities were not observed at the stations of Heping Township and Hualien City, which were near the epicenter and with PGVs equal to 65.7 cm/s and 56.3 cm/s, respectively.

2.3 Acceleration response spectra of selected strong ground motion stations

The response spectra of ground motions recorded at four representative stations, HWA019, HWA028, HWA048, and HWA051, were shown in Figure 4. Figure 3(b) gives the locations of the four stations. All the four stations sit on stiff sites, which have the average shear-wave velocity at depths between ground surface and 30 m (i.e., V_S30) not less than 270 m/s. Figure 4. also illustrates the design response spectra stipulated in Taiwan Building Seismic Design Code (TBSDC) 2022 (MLMA, 2022) and 1997, and the minimum seismic base shear force (denoted as VD) stipulated in the Taiwan Building Technical Regulations (TBTR) 1989 (MLMA, 1989). Moreover, VD/m is adopted for the illustration consistent with the unit of ordinate, where m is the mass of buildings. The design response spectra of TBSDC 2022, the present design code of Taiwan, have two types, one for the design basis earthquake (DBE) and the other for the maximum considered earthquake (MCE), i.e., 475- and 2500-year-return-period design response spectra, respectively (Figure 4).

At station HWA019 (Figure 4(a)), the N-S acceleration response spectra between 0.3 s and 1.3 s surpass most DBE design response spectra and even certain MCE design response spectra of TBSDC 2022. At station HWA051 (Figure 4 (c)), both N-S and E-W acceleration response spectra between 0.3 s and 1.3 s exceed most MCE design response spectra of TBSDC 2022. Notably, all observed N-S and E-W acceleration response spectra at the two stations (i.e., HWA019 and HWA051) are greater than the DBE design response spectra of TBSDC 1997, indicating the necessity for inspection of buildings constructed before 1999 Chi-Chi earthquake.

Figure 4(e) shows the pseudo-acceleration spectra recorded at ground motion station TAP025, near the mixed-use building complex in Nanjichang Night Market. Figure 4(f) shows the pseudo-acceleration spectra recorded at ground motion station TAP024, near Zhonghe Senior High School and the three street buildings in Tucheng District. Similarly, Figure 4(g) and Figure 4(h) illustrate the pseudo-acceleration spectra recorded at ground motion stations TCU011 and TCU009, near the traditional market in Daxi District and the residential building in Zhongli District, respectively. The pseudo-acceleration spectra displayed in Figures 4(e)-(h) are compared with their corresponding design response spectra for DBE and MCE. Accordingly, Figures 4(e)-(h) imply that buildings near the four ground motion stations should be intact or slightly damaged except for buildings with vibration periods of approximately 1.5-2.0 s near TCU011 and TCU009 ground motion stations, which may have been seriously affected.

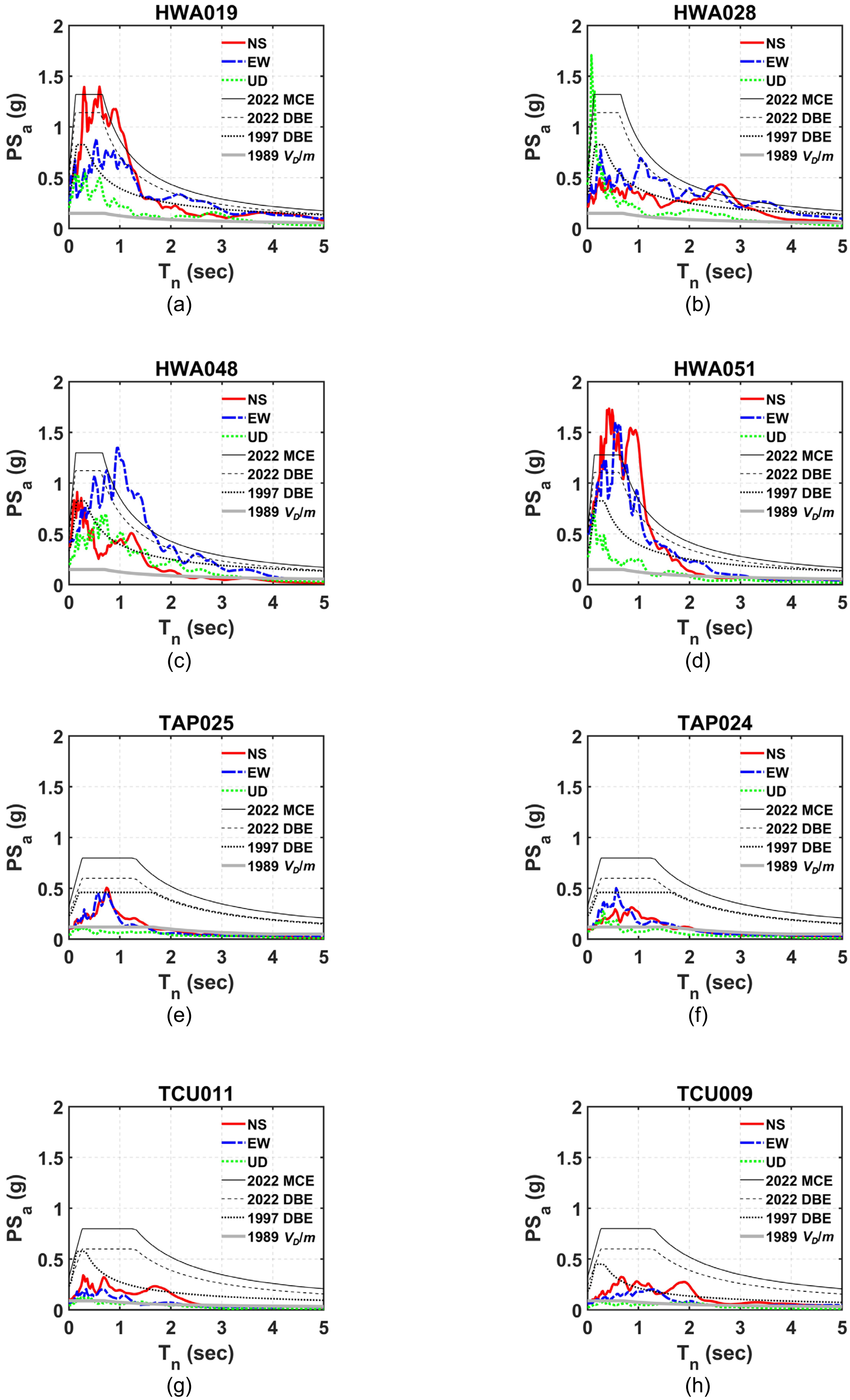


Figure 4. Pseudo-acceleration response spectra of all three components of ground accelerations observed at stations (a) HWA019, (b) HWA028, (c) HWA048, (d) HWA051, (e)TAP025, (f) TAP024, (g) TCU011, and (h) TCU009.

3 DAMAGED BUILDINGS IN THE TAIPEI METROPOLITAN AREA

By 9:00 p.m. on April 7, 42 buildings were marked with red placards and 70 with yellow placards across Taiwan (The Liberty Times, 2024a). Of the 42 buildings marked with red placards, two were in Taipei City, four in New Taipei City, four in Taoyuan City, and 32 in Hualien City. Because the Taipei metropolitan area, which is the political and economic center of Taiwan, this section focuses on the field inspection of the area, which is more than 100 Km away from the epicenter of the earthquake.

3.1 Mix-used building complex in Nanjichang Night Market

The inspected mix-used building complex in Nanjichang Night Market was once a renowned residential building built in 1964. The building complex was modern in terms of the living standards in Taipei during the 1960s (Figure 5(a)). During the rapid development of Taipei City, the building complex gradually became a corner of an aged-and-decayed metropolitan area. Figure 5(b) shows the current layout of Nanjichang Night Market. A comparison between Figure 5(a) and Figure 5(b) reveals that the complex comprises eight blocks. In addition, each block consists of two buildings: a front building and a rear building. Figure 5(c) depicts a typical five-story building within the complex, with the first story used as diners and the other stories being residential. Figure 5(c) also shows that a part of the roof is occupied by an added 6th story, which is probably illegal. Figure 5(d) shows a spiral stair installed between the front and rear buildings, representing a modern feature of the building complex in the context of 1960s' architectural style.

Figure 5(e) shows spalling of the concrete cover at the bottom pillar of a spiral staircase. The cross-section of the pillar was a polygon with a diagonal dimension of approximately 250 cm. The spacing between stirrups was 30 cm. Additionally, the exposed reinforcements were severely rusted. Nevertheless, no obvious cracks occurred at the confined concrete, nor was there any buckling of reinforcements (Figure 5(e)). As indicated by the gaps between the stair and the building (Figure 5(f) and Figure 5(g)), the pillar was isolated from the building structure. In other words, the seismic force was not directly transmitted between the building and the stair pillar. Figure 5h indicates that the bottom concrete of a stair was significantly deteriorated with spalling concrete cover and efflorescence. Figure 5(e) — Figure 5(h) indicate that damage to the pillar was minor, which can probably be attributed to deterioration of the concrete subjected to small inertia forces resulting from the earthquake. Figure 5(i) shows that in addition to shoring up with a temporary steel column, a damaged column of the building complex was retrofitted. Because of the retrofitting technique used for the damaged column (perhaps replacing falling concrete cover with fresh concrete), the damage state of the column was not severe. Overall, despite minor damage, the structural integrity of the building complex in Nanjichang Night Market was retained under the seismic event. Nevertheless, the issue of durability of this 60-year-old building complex should be addressed in urban development planning.

Figure 5. (a) Historical image of the building complex (CommonWealth Magazine, 2024), (b) map of Nanjichang Night Market, (c) typical appearance of the building complex, (d) spiral stair between front and rear buildings, (e) spalling of concrete cover at the pillar base of the spiral stair, (f) gap between spiral stair and wall, (g) gaps between the spiral stair and slab/wall, (h) deterioration of a slab, and (i) retrofitting of a reinforced concrete column alongside a temporary steel support.

3.2 Zhonghe Senior High School

The seismic resilience of the buildings at Zhonghe Senior High School was evaluated and retrofitted in accordance with requirements of a nationwide project for seismic retrofitting of school buildings across Taiwan. The nationwide project was conducted by Taiwan's Ministry of Education in collaboration with the NCREE from 2009 to 2022. Figure 6(a) shows a segment of the previous retrofitting effort, which reduced the unsupported length of an outdoor reinforced concrete (RC) column in the administration building by adding steel beams. Figure 6(b) shows that the edge ceiling of the 7th story of the administration building collapsed, which typically results from the edge ceiling pushing against the wall under the exertion of earthquakes. This figure also shows that a vent pipe, originally concealed above the ceiling, was dislodged and thrust through the ceiling. On the 2nd story of the administration building, a partition brick wall cracked in two diagonal directions (Figure 6(c)). Figure 6(d) indicates that a longitudinal crack occurred at the bottom of a wide beam; this longitudinal crack was along the contact surface between two adjacent beams belonging to separate buildings. Because the two school buildings were arranged perpendicular to each other, different vibration periods of the buildings resulted in cracks at the interface. Soft material such as styrofoam that is typically used in expansion joints between such buildings was not observed. Figure 6(e) indicates that shear cracks occurred in short columns. Subsidence was also observed on the step of a stair on the long side of an indoor swimming pool (Figure 6(f)). Nevertheless, because both the swimming pool itself and the structure housing the swimming pool remained intact, the influence of the observed subsidence was limited. Except for the shear cracks and the failure of nonstructural components shown in Figure 6(e) and Figure 6(b), the overall seismic performance of the inspected buildings at Zhonghe Senior High School was satisfactory. This proves the effectiveness of the seismic retrofitting conducted before the Hualien earthquake of 3 April 2024.

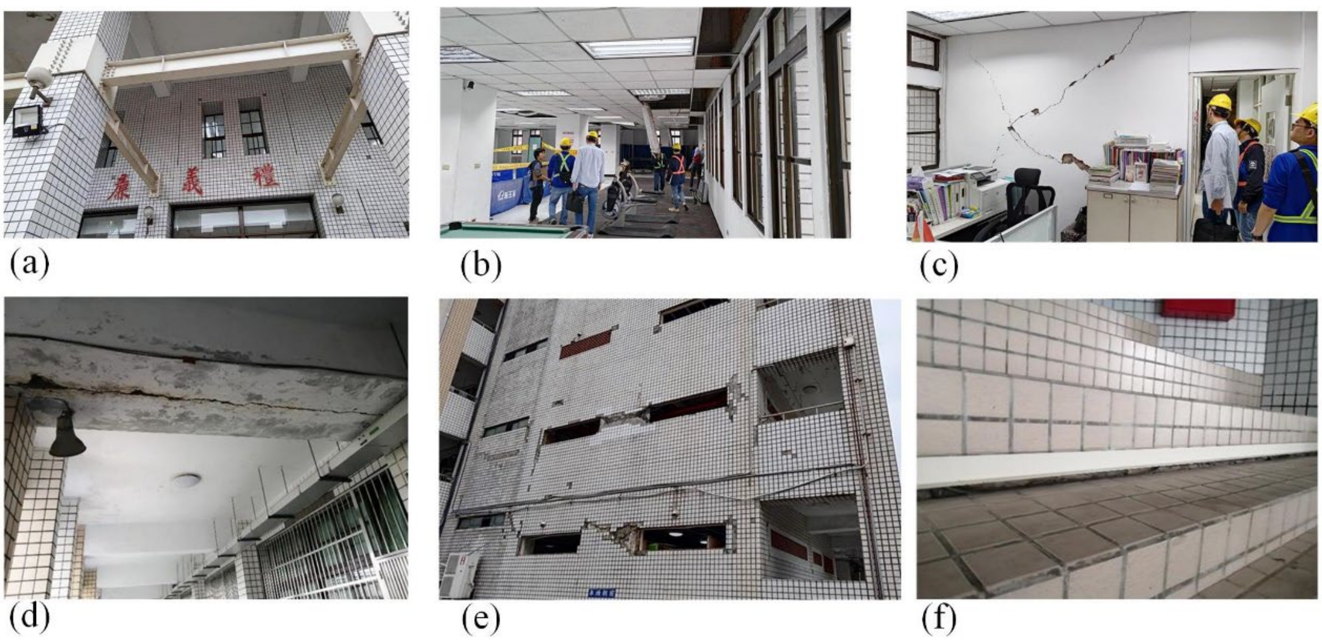


Figure 6. (a) Previous seismic retrofit work, (b) collapse of edge ceiling and vent pipe, (c) shear cracks in partition brick wall, (d) horizontal crack along the interface of two side-by-side beams, (e) shear cracks in short columns, (f) subsidence on a stair step.

3.3 Street buildings in Tucheng District of New Taipei City

Three street buildings were inspected in the Tucheng District of New Taipei City. These buildings are situated within approximately one kilometer. The inspection findings for each building are detailed below.

3.3.1 The first street building

The first street building is a 32-year-old building with eight stories and one basement. The building is located at the intersection of two perpendicular streets (Figure 7(a)). Figure 7(b) presents a close-up view of Figure 7(a) to clearly display the three-span temporary shoring for two damaged columns due to the seismic event. According to the structural plan (Figure 7(c)), the two damaged columns are denoted as C2 and C3, each measuring 50 cm × 50 cm and are specifically highlighted in Figure 7(b) and Figure 7(c). Figure 7(d) and Figure 7(e) show the damage states of columns C2 and C3, respectively. The upper halves of the confined concrete of both columns C2 and C3 were crushed. In addition, the main reinforcements were buckled. Figure 7(d) reveals that a drainage pipe with a diameter of approximately 10 cm was embedded in the center of column C2. Additionally, the maximum spacing of stirrups of column C2 was approximately 40 cm (Figure 7(d)). According to the structural design drawings, the main reinforcements of columns C2 and C3 were designed as 20-ϕ32 and 8-ϕ32+12-ϕ25, respectively. Hence, if the main reinforcements were uniformly distributed over the four sides of the columns, there should have been six reinforcements on each side of the column. However, Figure 7(d) and Figure 7(e) show that the number of reinforcements of columns C2 and C3 were insufficient. According to the structural design drawing, the spacing of stirrups of columns C2 and C3 should be 15-25 cm, but the 40 cm spacing of stirrups of column C2 (Figure 7(d)) significantly exceeded the design spacing. Therefore, the poor construction quality of the street building was probably a critical factors leading to its structural failure.

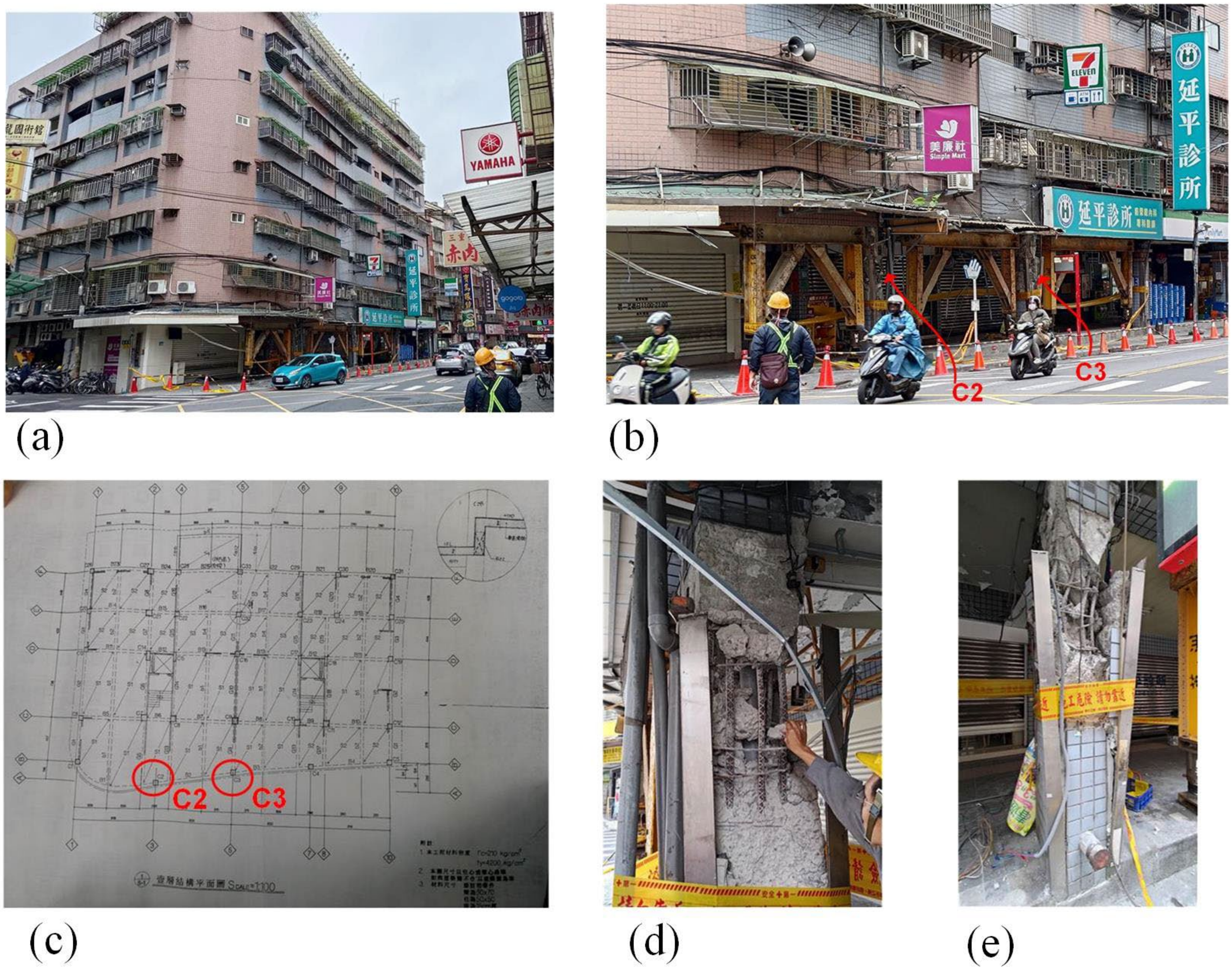


Figure 7. (a) Photograph of the first street building, (b) a close-up of (a), (c) structural plan, (d) column C2, and (e) column C3.

3.3.2 The second street building

Figure 8(a) shows that the second street building is a five-story structure with an additional 6th story. Moreover, Figure 8(a) indicates that the first story was used as shops and the upper stories were used for residence, which is common for street buildings in Taiwan. In addition, the space between the outdoor columns and the shop fronts constitutes an arcade (or corridor) for pedestrians. Figure 8(a) also indicates that the left half and the right half of the added 6th story seem to differ. In other words, the additional weight resulting from the added 6th story might be unevenly distributed. Five-span temporary shoring had been erected on the first story along the street (Figure 8(a)). Figure 8(b) offers a view from the arcade toward the street. Figure 8(b) shows that the light steel and decorating material in the arcade were damaged and collapsed. Figure 8(c) shows the damage to the brick wall of a staircase, which was used by residents of the upper stories. Figure 8(d) and Figure 8(e) show crushed confined concrete and buckled reinforcements at the upper halves of two columns. The damage patterns of the second street building (i.e., Figure 8(d) and Figure 8(e)) were similar to those of the first street building (i.e., Figure 7(d) and Figure 7(e)). These similar damage patterns observed across the street buildings reveal that the exterior columns of corridors of street buildings are vulnerable to earthquakes. Accordingly, enlarging the cross sections of corridor columns or adding braces along the corridor could effectively enhance the seismic retrofitting of street buildings.

Figure 8. (a) The second street building, (b) an outlook from the arcade toward the street, (c) a damaged brick wall of a staircase, (d) and (e) damaged columns.

3.3.3 The third street building

The third street building is a 41-year-old five-story building (Figure 9(a)). Because the building is located in lanes rather than on a main road, the first story is used for residence, which differs from those of the first and second street buildings. Figure 9(b) shows a horizontal crack in an indoor brick wall. The horizontal crack appeared along the interface between the bottom of a beam and the top of a wall. Figure 9(c) shows the cracks in a brick wall of a staircase. The shear cracks in the brick walls shown in Figure 8(c) and Figure 9(c) demonstrate the role of brick walls in resisting earthquake loads. Notably, out-of-plane toppling of brick walls was not observed during this seismic reconnaissance. This observation suggests that the brickwork adopted in Taiwan is generally effective in preventing brick walls from toppling out of plane, a phenomenon frequently observed elsewhere in the world during earthquakes.

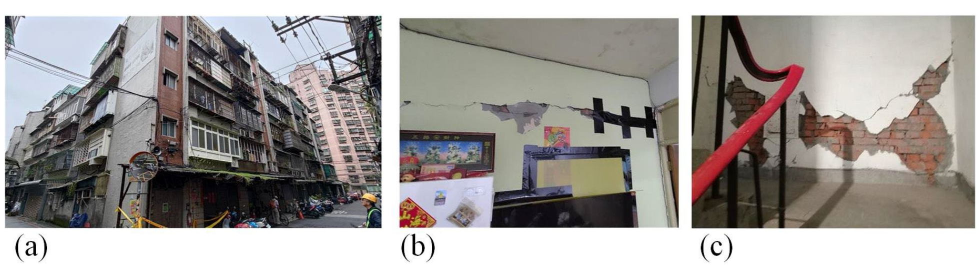


Figure 9. (a) The third street building, (b) a horizontal crack in an indoor brick wall, (c) damaged brick wall of a staircase.

3.4 Traditional market in Daxi District of Taoyuan City

The traditional market inspected in Daxi District of Taoyuan City is surrounded by residential buildings. In other words, the market is concealed within a courtyard (Figure 10(a)). This market, existing for over 40 years, comprises a single-span RC structure in the short direction and a multiple-span structure in the longitudinal direction (Figure 10(b)). In addition, the transverse girders are interconnected at their midpoints with small beams (Figure 10(b)). In addition to the traditional market on the ground floor, there is an upper second story, which serves as residential space (Figure 10(c)). The most notable damage observed was a shear cut at the top of a corner column (Figure 10(d)). Figure 10(e) shows a close-up of Figure 10(d) for clarity. The steel columns shown in Figure 10(d) were temporary shoring erected after the seismic event. There is a staircase located at the opposite longitudinal end (Figure 10(f)). The staircase consists of two RC columns and one brick wall. The upper half of one of the two staircase columns was also damaged (Figure 10(f)). Figure 10(g) shows a close-up of Figure 10(f) for clarity. Because only one end of the market features a staircase, the structure of the market is asymmetric in the transverse direction (i.e., the single-span direction). This asymmetry likely caused the severe damage to the corner column, which potentially experienced additional large deformation due to rotational response. The presence of a first-story traditional market with a second-story residence is unusual, and it is questionable whether the weight of the second story was appropriately considered during design of the market.

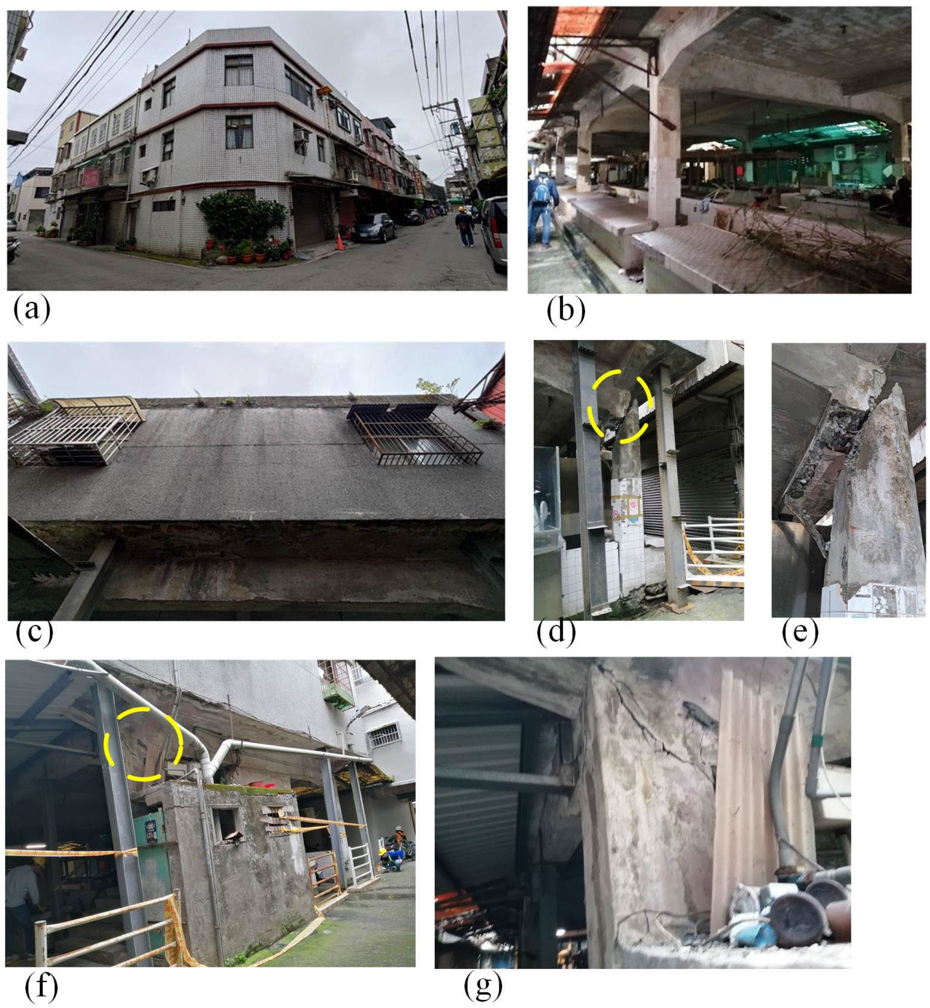


Figure 10. (a) Residential buildings encircling the market, (b) overview of the market, (c) exterior wall of the second story of the market, (d) shear cut at the top of an RC column, (e) close-up of (d), (f) staircase at one end of the market, and (g) close-up of (f).

3.5 A residential building in Zhongli District of Taoyuan City

The inspected residential building in Zhongli District of Taoyuan City was constructed in 1991 (Figure 11(a) and Figure 11(b)). It features seven stories and one basement. The first story was use as a supermarket. A two-story one-span extension was constructed in front of the seven-story main structure. Figure 11(c) displays a neighboring building similar to the inspected building. Except for the balcony on the second story, the front elevation of the neighboring building is similar to the inspected building. Therefore, comparing the front elevation of the inspected building with that of the neighboring building reveals that the two-story one-span structure appears to be an additional feature rather than an original part of the inspected building, rendering it vertically irregular. Furthermore, according to conversations with residents in the neighborhood of the inspected building, the partition walls in the first story of the original building were removed to provide space for the supermarket. If this is true, the preservation of the first-story strength of the inspected building is in doubt.

Because the inspected building was marked with red placards, the residents were evacuated and the reconnaissance team was prevented from entering it. The overall appearance of the building seemed in order except for some tiles that were spalling (Figure 11(d)). However, a photograph captured by the media (The Liberty Times, 2024b) revealed that a column inside the first-story supermarket underwent shear failure (Figure 11(e)). Potential remolding of the building likely contributed to the shear failure of the column. It is also worth noting that the side of the column perpendicular to the shear cracks appeared to be intact (Figure 11(e)). This observation suggests that either the seismic demand (i.e., earthquake load) was much greater or the seismic capacity of the inspected structure was much less in the direction parallel to the shear cracks than in the direction perpendicular to the cracks. More definite reasons for the column failure will emerge when the building is inspected thoroughly and related information regarding structural design is accessible.

Figure 11. (a) and (b) Photographs of the residential building, (c) a similar building neighboring the inspected building, (d) fallen tiles from an exterior column, and (e) shear cracks in a column within the supermarket (The Liberty Times, 2024b).

4 DAMAGED BUILDINGS IN THE EPICENTRAL AREA (HUALIEN COUNTY)

The earthquake caused severe damage to at least 84 buildings in the epicentral area. It is worth noting that the most affected buildings were those built before the 1999 Chi-Chi earthquake. Significant changes and improvements occurred in design and construction practices in Taiwan after the 1999 earthquake (Chai et al., 2009). Therefore, Taiwan is better prepared than it was in 1999, as only minor nonstructural damage was seen in buildings constructed after the Chi-Chi earthquake.

4.1 Buildings structured with reinforced concrete frames

In the field inspection, the most common structural system in urban areas was moment-resisting reinforced concrete (RC) frames. The system typically consisted of rectangular elements (beams and columns). The second most frequently used system was confined and unconfined masonry. Single-floor wood buildings were also observed. Most residential buildings inspected were four to ten stories high, with each story typically containing two to six apartments.

The building plans have a rectangular layout, and each building is constructed as an independent structure, situated adjacent to the next building without any collisions. The structures were constructed using reinforced concrete (RC) with concrete floors and masonry infills walls. Additionally, some buildings used reinforced concrete walls combined with moment-resisting frames as a structural solution.

No high-rise buildings were found during the post-earthquake field inspection in the epicentral area. A few steel structures were identified during the visit, with no damage to structural elements nor non-structural components. Similarly, no precast beams and columns were identified as part of the structural system.

The most common structural irregularities identified were soft-story buildings. These irregularities often led to severe damage or collapse due to the weaker lower stories having less stiffness and resistance. This condition occurred because the ground floor mainly contains open spaces, while the upper stories have infill walls that increase the lateral stiffness. As a result, there is a change in stiffness between adjacent inter-stories.

In Figure 12 and Figure 13, two cases of building collapses are shown caused by a weak first story. They occurred approximately 500 meters apart. The response spectra of the seismic ground motions recorded by the three closest stations to the buildings are shown in Figure 4(a), (b), and (c) and are compared to DBE and MCE design spectra. The closest station (HWA019) is around 300 meters from the building depicted in Figure 4. Therefore, the design spectra and the distances to the stations are the same. Even though the ground motions were recorded at specific locations, the magnitudes, distance from the source, and source mechanisms are consistent with those influencing the maximum demand in the buildings. It is important to note that the north-south component (NS) of the closest station (HWA019), as shown in Figure 4(a), corresponds to the demand defined by the MCE. This finding emphasizes the importance of the seismic demands imposed by the quake.

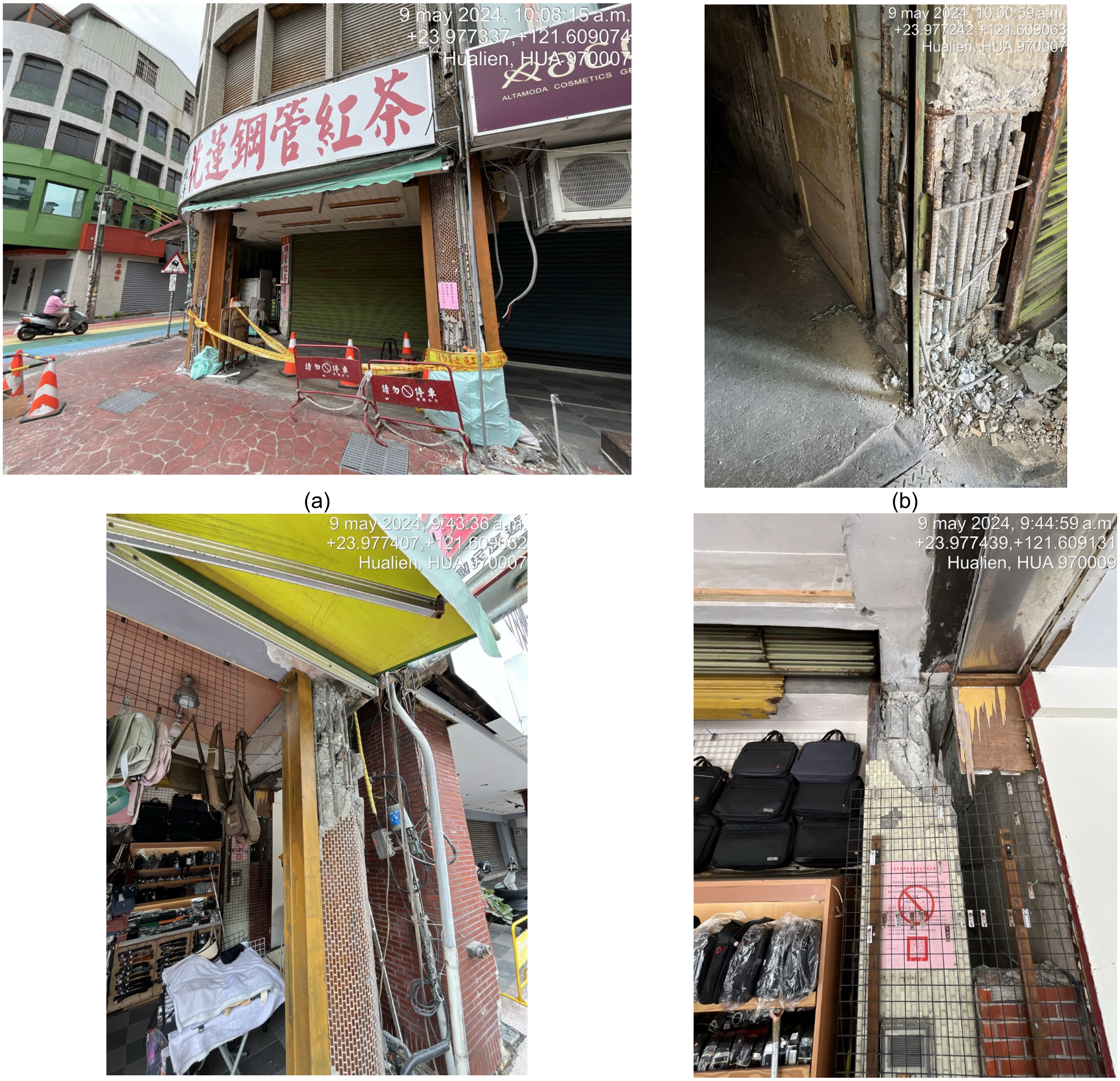
(a) (b)

Figure 12. Damaged 9-story building (coord. 23.9744, 121.6118) due to a first soft story: (a) pre-earthquake state (credit: Google Maps), and (b) post-earthquake state.

(a) (b)

Figure 13. Damaged 4-story building (coord. 23.9726, 121.6057) due to a first soft story: (a) pre-earthquake state (credit: Google Maps), and (b) post-earthquake state.

Many buildings have shops or similar commercial spaces on the ground floor, often with a large entrance hall and few dividing walls (Figure 12(a) and Figure 13(a)). This type of structural irregularity is known as soft story and it is one of the most commonly used structural configurations in collapsed buildings in other earthquakes (Ozkula et al., 2023; Tapia-Hernández et al., 2024). For example, Figure 14 shows a 4-story corner building with a soft ground story, highlighting the vulnerability of this configuration. This building was classified as the red-tagged building because of the severe structural damage in the reinforced concrete column of the ground floor.



(a) (b)

(c) (d)

Figure 14. Soft ground story with structural damage in columns (coord. 23.9773, 121.6092): (a) general view, (b), (c), and (d) details of damaged columns.

In the inspected buildings, eccentric loading on columns and beams was not an unusual structural solution. Namely, the loads applied on the structural element are not aligned with its central axis, causing bending stresses in addition to the direct axial load. Eccentric loading can lead to increased bending stresses, P-Delta effects, unexpected redistribution of forces, and, therefore, a reduction in load-carrying capacity.

Examples of damage in reinforced concrete columns are depicted in Figure 15. It is worth noting that the cracking in these columns is caused by increased bending moments due to the horizontal offset, and other factors related to the detailing of the reinforcement steel. The combination of offset axial and bending stress might impact the behavior and capacity of columns under seismic demands and should be carefully considered during the design process.

(a) (b) (c)

Figure 15. Beams not aligned with the central axis of columns: (a) building under construction (Coord. 23.9751, 121.6149), (b) eccentricity in an RC column (Coord. 23.9760, 121.6125), and (c) damage in a circular RC column (coord. 23.9781, 121.9700).

As shown in Figure 16, the masonry infill walls were usually built using solid clay bricks measuring 195×95×55 mm for confined and unconfined walls. The bricks seemed to have been fired at high temperatures, resulting in a strong and uniform material. It was common to observe heavy façades constructed with unconfined masonry walls and, in some cases, with lightweight foamed blocks supported by concrete slabs acting as cantilevers. Additionally, reinforced concrete piers and spandrels were seen in façades.

(a) (b) (c)

Figure 16. Behavior of infill walls: (a) bricks for the reconstruction, (b) unconfined infill wall, and (c) damaged masonry wall.

The strength degradation and lateral stiffness, as well as the primary mode of failure in walls, depend on boundary constraints, material characteristics, the combined effect of axial forces, height-to-width ratio, and lateral loads (Espinosa-Cazarín et al., 2023). Walls may fail due to sliding, rocking, diagonal shear, or local buckling in extruded pieces. Infill walls are particularly susceptible to high damage due to their interaction with reinforced concrete frames (Tapia-Hernández et al., 2024), regardless of the material type (Figure 16(c)).

4.2 Reinforcement detailing

In buildings structured with reinforced concrete frames, the dynamic energy is typically absorbed through plastic hinges at the ends of the structural components. These hinges follow specific detailing rules and recommendations based on specialized seismic codes, determined by experimental and analytical studies. These rules guide the minimum and maximum reinforcement ratios, spacing, diameter, hooks, stirrups, splices, and other reinforcement layout and placement aspects.

During the field inspection, it was discovered that the old concrete did not meet the strict regulations, specifically concerning the size and quality of the aggregates. The reinforced concrete columns where the concrete used river rocks as aggregates and sea sand containing chloride and other substances are shown in Figure 17, which significantly impact the material's mechanical properties.

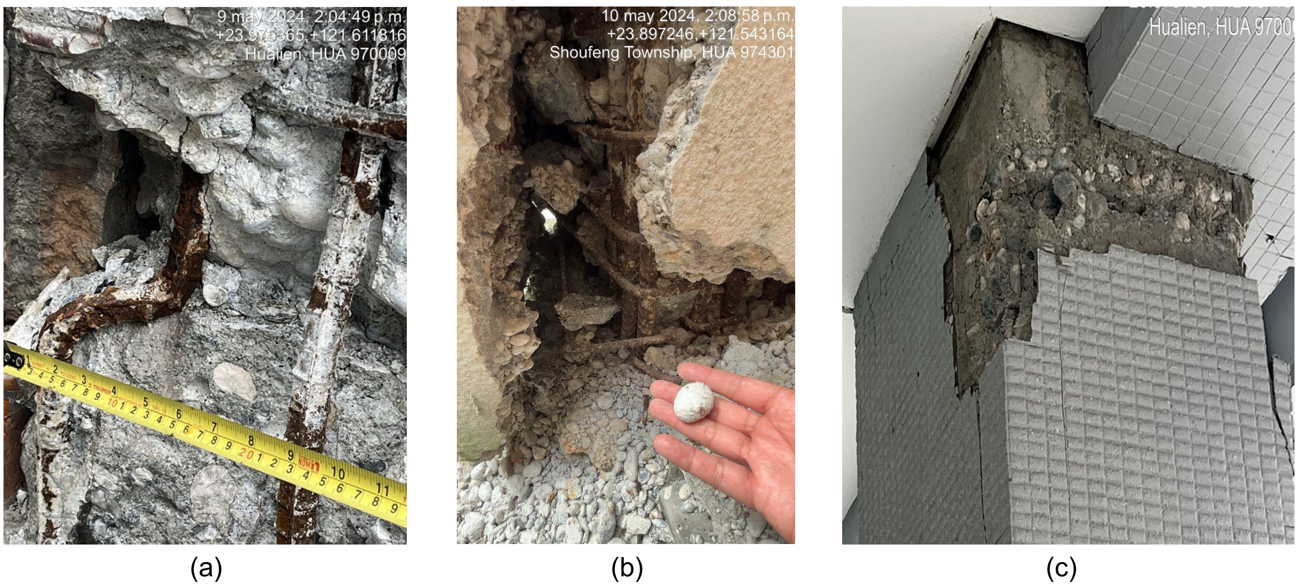


Figure 17. Improper aggregate and sand in the concrete mixture: (a) plastic hinge with river stone (coord. 23.9759, 121.6127), (b) damaged RC wall (coord. 23.9751, 121.6116), and (c) RC column (coord. 23.9759, 121.6127).

The inspection found corrugated (non-smooth) steel bars, even in old structures. Nevertheless, there were issues with the reinforcement continuity or the anchorage length between the slabs, beams, and columns (Figure 18(a)). It is understood that when column heights exceed the standard bar lengths available, it is necessary to splice the steel bars end-to-end by overlapping. Proper splicing and tying of the rebar are crucial for the integrity of the concrete components, especially in areas where inelastic incursion is expected. It is advisable to place the lap splice in the middle third of the columns to prevent stress concentrations at the top or bottom of the column.

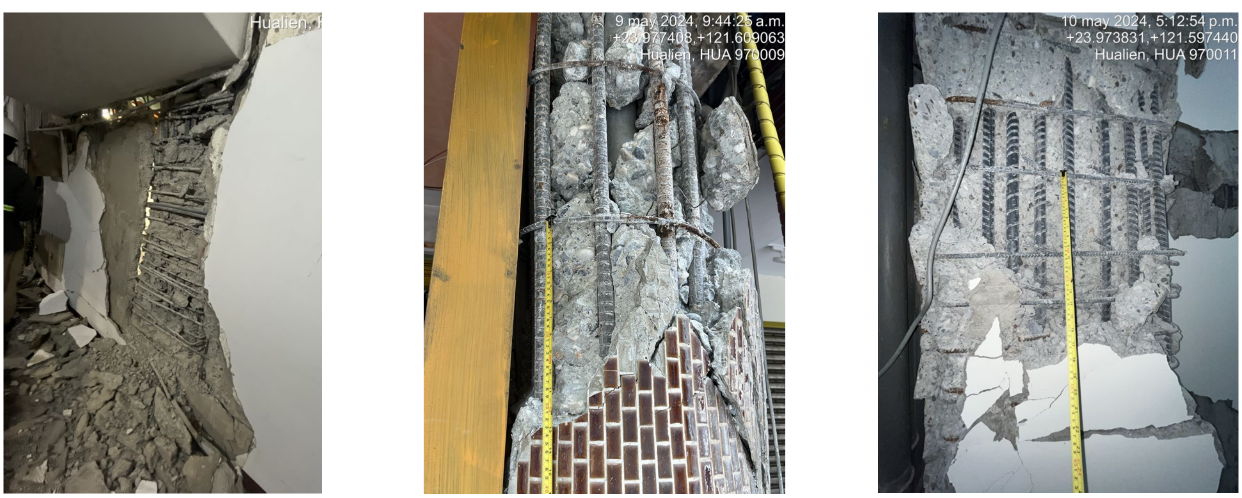
Rebar couplers connect two reinforcing bars in the longitudinal direction, creating a mechanical splice. They are beneficial for reducing congestion in confined spaces and conserving rebar length. The use of coupler splicers for the mechanical overlapping in a damaged column is depicted in Figure 18(b), where all the coupler splicers located at the hinge rotation of the column, promoting damage concentration. Thus, placing the overlaps in areas with low bending demands is important to prevent the creation of weak points (ATC, 1996).

Additionally, in certain cases, the longitudinal steel bars were not positioned inside stirrups, leading to insufficient confinement of the core steel, as shown in Figure 18(c). Closed ties or stirrups should be formed in a single piece by looping standard stirrups or tie-end hooks around a longitudinal bar.

(a) (b) (c)

Figure 18. Improper details of the reinforcing bars: (a) congestion of steel bars in plastic hinge, (b) coupler splicers at the hinge rotation, and (c) longitudinal steel bars not joint to the stirrup.

During the field inspection, it was observed that in some cases, stirrups were inadequately anchored with 90° hooks instead of the specified 135° hooks. This resulted in ineffective confinement when the cover concrete was lost (Figure 19(a)). The shear strength the concrete provides decreases as bidirectional bending rotations and crack widths increase. Placing the rebar according to modern seismic codes is important. An inadequate separation or insufficient stirrups in relation to the longitudinal bars might lead to damage concentrations, as shown in Figure 19(b) and (c).



(a) (b) (c)

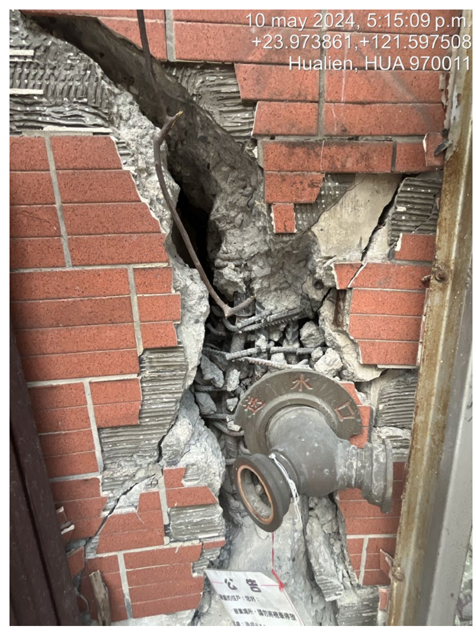
Figure 19. Inadequate stirrup detailing, typical of pre-Chi Chi Earthquake: (a) 90° hooks in stirrups, (b) improper stirrup separation, and (c) insufficient shear capacity.

It is important to note that in some cases, the integrity of the columns was compromised due to pipes passing through the concrete core, as depicted in Figure 20. The presence of the pipes led to reduced strength for both axial and flexural capacity due to non-uniform stress distribution. Additionally, inadequate steel bar details resulted in excessive flexural cracking in the concrete components.

(a)

(b)

(c)



(d)

Figure 20. The presence of pipes inside RC columns: (a) PVC drainage pipe, (b) water pipes, (c) and (d) wall hydrant

4.3 Damage to schools

The school buildings generally performed well during the earthquake, mostly due to an ambitious retrofitting program launched by the authorities of Taiwan in 2009. However, three schools were identified with damage as discussed below.

4.3.1 The Mingli Elementary School

Mingli Elementary School had previously been retrofitted due to damage from earlier earthquakes. During field inspections, some horizontal cracking was identified in reinforced concrete shear walls, as shown in Figure 21. The design and response spectra of the nearest station (HWA019) are shown in Figure 4(a), located only 652 meters from the school's position. Due to the high imposed demands, it is concluded that more severe damage was expected without the structural retrofit. The damage was mainly identified in the junction of existing and added structural elements.

(a) (b) (c)

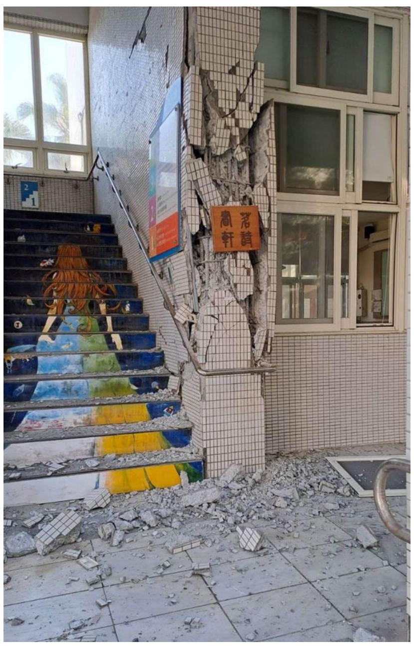
Figure 21. Affectations to the Mingli Elementary School during the earthquake: (a) cracking on a wall at the stairs, (b) cracking on a wall at a classroom, and (c) cracking on the restrooms

4.3.2 The National Hualien Girls' Senior High School

The National Hualien Girls' Senior High School consists of several buildings ranging from two to four stories height. One building was severely damaged, while the others showed only minimal affectations. The building that suffered severe affectations was not reinforced due to it held a safety certificate based on an early method for quick evaluation, which differs from NCREE's evaluation method (Hwang et al., 2022). Unfortunately, that structure experienced severe damage in the reinforced concrete columns due to short-column mechanism, leading the authorities to decide to demolish the building (Figure 22(a)). The distance from the school to nearest station (HWA019) was 537 meters (Figure 4(a)), clearly indicating that the expected damage was significant, which was the case for the building that was demolished. Nevertheless, the other buildings did not sustain significant damage, only some effects near the construction joints between buildings (Figure 22(b)). Therefore, it can be concluded that, apart from the demolished building, the school performed well.

(a)

(b)



(c)

(d)

Figure 22. Affectations to the National Hualien Girls' Senior High School: (a), (b), (c), and (d) severely damaged building that had to be demolished (https://www.cna.com.tw/news/ahel/202404030165.aspx).

4.3.3 The Chemistry Building of the National Dong Hwa University

The Chemistry Building of the National Dong Hwa University sustained both structural and non-structural damage during the earthquake (Figure 23(a) and (b)). Furthermore, a fire that broke out after the earthquake caused significant destruction. The laboratories, equipment, and non-structural components suffered considerable losses (Figure 23(c) and (d)). The distance from the University to the nearest station (HWA051) was 3,860 meters. Analysis of the response spectra of HWA051 (Figure 4(d)) indicated that significant damage was expected, as the spectral accelerations exceeded the MCE spectra by a significant range for vibration periods shorter than 1.2 s.

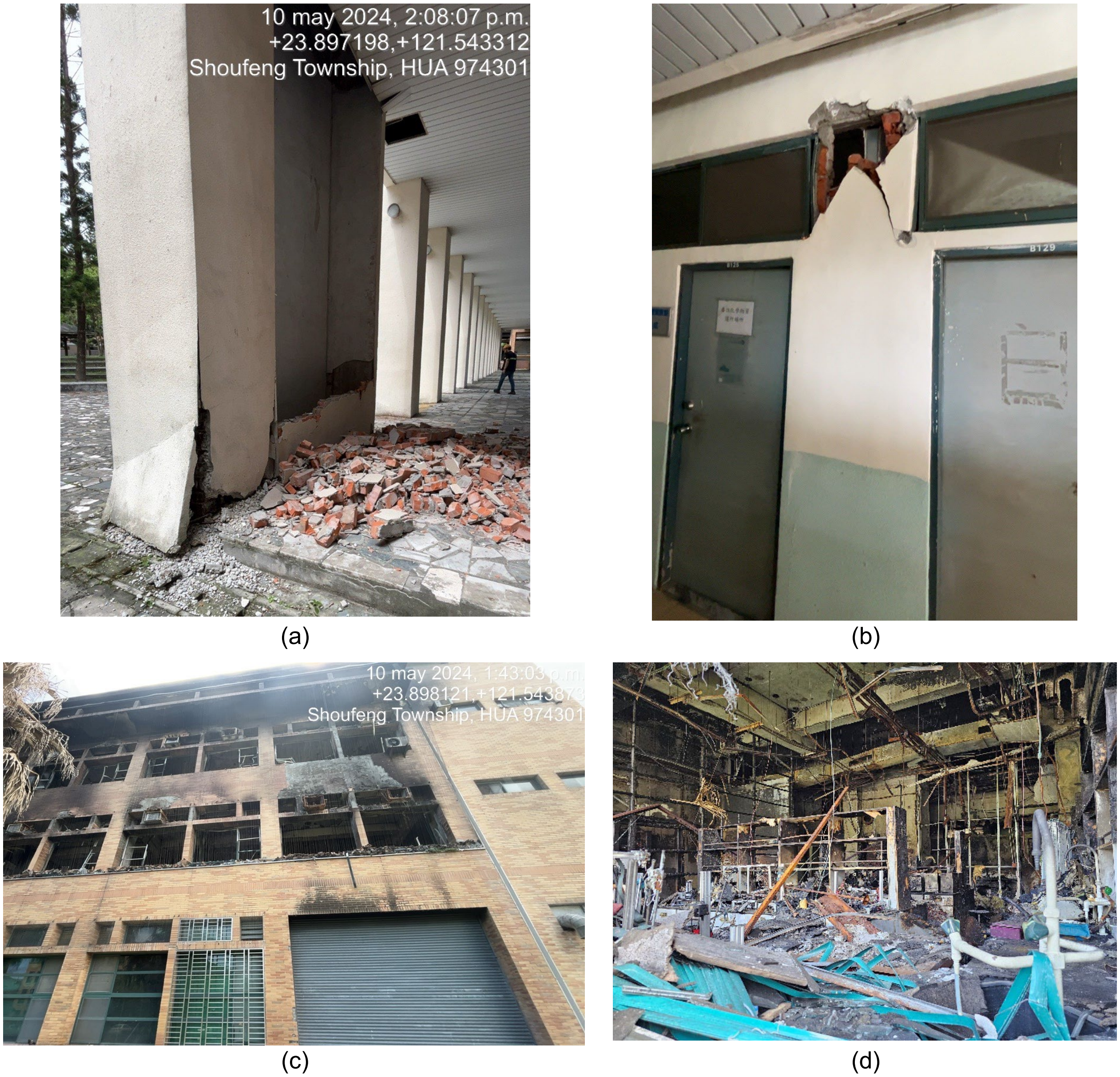


Figure 23. Chemistry Building of the National Dong Hwa University: (a) moderate damage to a column along with failure of a non-structural wall, (b) damage to non-structural wall, (c) main façade of the Chemistry Building, and (d) damage inside the laboratories.

5 UNDAMAGED BUILDINGS

5.1 Buildings retrofitted with added or strengthened RC members

Based on lessons learned from past major earthquakes, the primary seismic vulnerability of private buildings lies in soft-weak story structures, inadequate structural systems, and poor construction quality. In response, the NCREE, under the mandate of Taiwan's Ministry of the Interior's Land Management Agency, initiated the "Seismic Weak-Story Retrofitting Project Office of Private Buildings" in 2019 (NCREE, 2019). This office aims to promote seismic weak-story retrofitting, establish a mechanism for reviewing retrofit designs, provide educational training for seismic retrofitting professionals, and provide information and assistance to the public. The seismic weak-story retrofitting project enables residents to enhance building seismic resistance swiftly during the extended wait before urban renewal or complete retrofitting. The weak-story retrofit plans are categorized into three options: A, B, and C. Plan A aims to resolve weak-story issues. Plan B not only addresses weak-story problems but also upgrades to 80% of current code (i.e., TBSDC 2022) standards. Plan C focuses on restoring damaged members (columns, beams, walls, and slabs) to their pre-earthquake condition.

After the 0403 Hualien earthquake, the survey team inspected three retrofitted cases located in Hualien City and funded under the retrofitting project. The on-site survey findings from the three retrofitted buildings are introduced below.

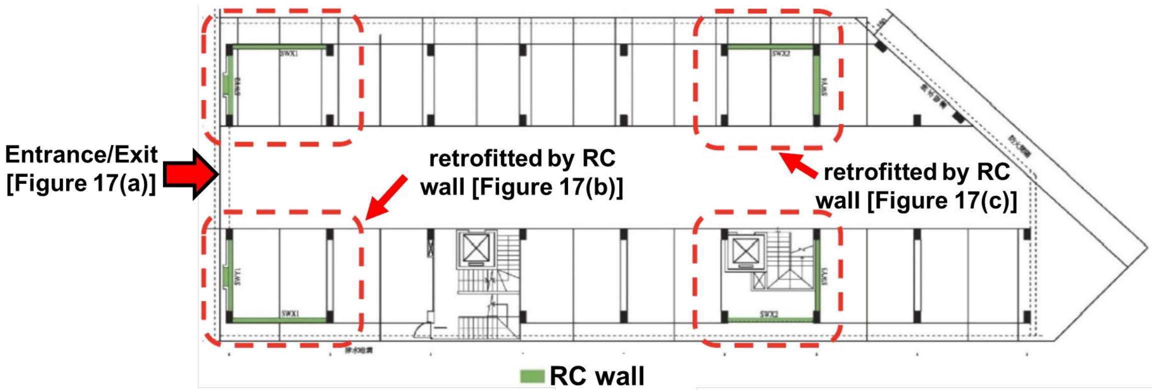
5.1.1 Retrofitted Building I: Six-story RC residential building retrofitted under Plan A

This case involves a six-story RC building completed in 1993 (Figure 24(a)). The first story serves as a parking lot, while the second to sixth stories are residential units. This building was retrofitted under Plan A, with a total cost of approximately US$53,700 (including design and supervision) and a work period of 51 days. Shear walls were added on the first story to minimize the impact on residents. The residents reported that the retrofitting work did not disrupt their daily lives. The post-retrofit building is shown in Figure 24(b), and the strengthened locations on the structural plan are shown in Figure 24(c). On-site investigation revealed no significant damage to the main members, as shown in Figure 25.

According to house price registration data on a real estate website (LeWu, 2024a), Retrofitted Building I contains 36 households. Considering without government subsidies, the total retrofitting cost shared by each household is calculated to be US$1,500. Assuming each household owns 100 m² of usable space, the retrofitting cost is US$15/m^2. In addition, the average selling price of Retrofitted Building I in recent years was US$1,560/m^2 (LeWu, 2024a), indicating that the cost-effectiveness ratio (CER) of the retrofit project is approximately 104. Therefore, the retrofit plan not only satisfactorily improves the seismic resistance of the building but also economically protects residents' property.

(a)

(b)

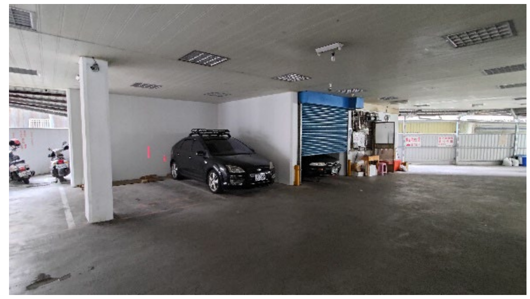


(c)

Figure 24. Information pertinent to Retrofitted Building I: (a) before retrofit, (b) after retrofit, (c) structural plan and retrofitted locations (NCREE, 2019).

(a)

(b)



(c)

Figure 25. On-site survey status of Retrofitted Building I after the 0403 Hualien earthquake: (a) entrance/exit, (b) and (c) retrofitted with RC walls.

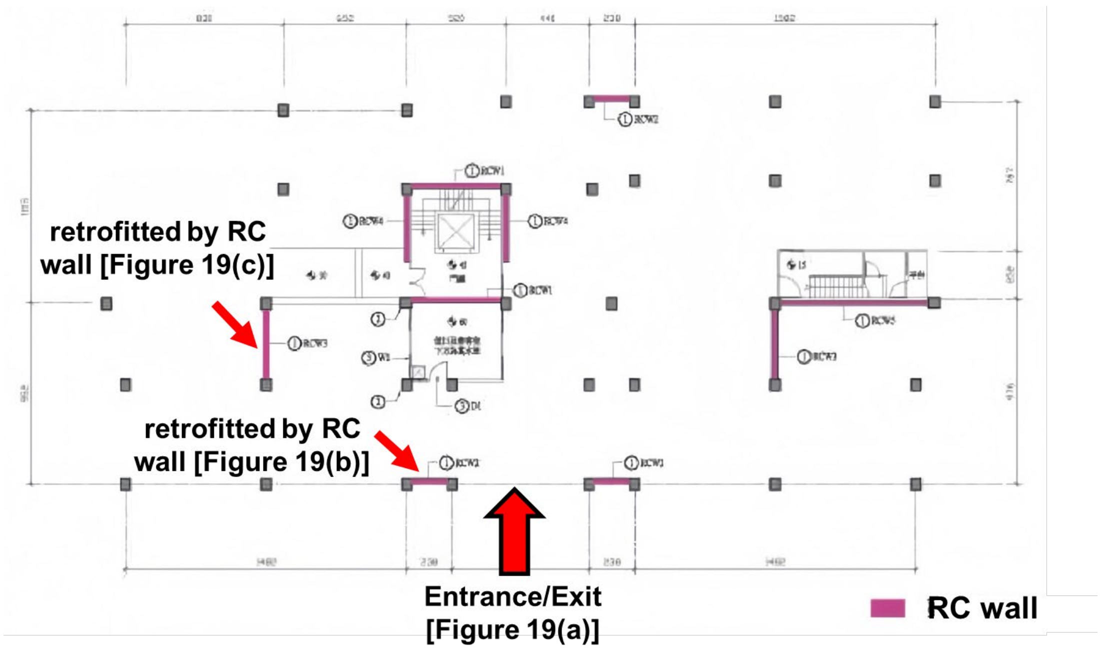
5.1.2 Retrofitted Building II: Six-story RC residential building retrofitted under Plan A

This case involves a RC building with six stories above ground and one underground story, completed in 1991 (Figure 26(a)). The underground story houses the transformer room and reservoir, the first story is a parking lot and contains a duty room, and the second to sixth stories are general residences. This building was retrofitted under Plan A, with a total cost of approximately US$95,800 (including design and supervision) and a work period of 71 days. Shear walls were added on the first story to minimize the impact on residents. The residents reported that the retrofitting work did not disrupt their daily lives. The post-retrofit building is shown in Figure 26(b), and the strengthened locations are shown on the structural plan in Figure 26(c). On-site investigation revealed no significant damage to the main members (Figure 27).

According to house price registration data on the real estate website (LeWu, 2024b), Retrofitted Building II contains 45 households. Considering without government subsidies, the total retrofitting cost shared by each household is US$2,130. Assuming each household owns 100 m² of usable space, the retrofitting cost per square meter is US$21. Additionally, the average selling price of Retrofitted Building II in recent years was US$1,740/m² (LeWu, 2024b), indicating that the CER of the retrofit project is approximately 83. Therefore, the retrofit plan not only satisfactorily improves the seismic resistance of the building but also economically protects residents' property.

(a)

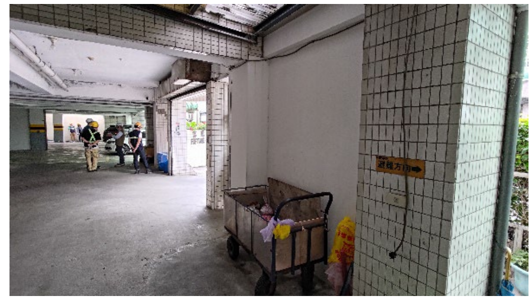
(b)



(c)

Figure 26. Information relating to Retrofitted Building II: (a) before retrofit, (b) after retrofit, (c) structural plan and retrofitted locations (NCREE, 2019).

(a)



(b)

(c)

Figure 27. On-site survey status of Retrofitted Building II after the 0403 Hualien earthquake: (a) entrance/exit, (b) and (c) retrofitted with RC walls.

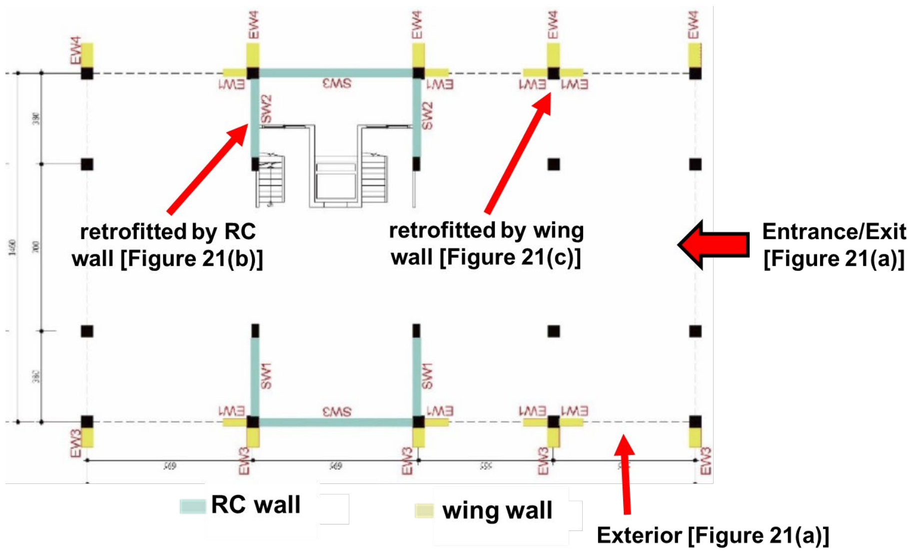
5.1.3 Retrofitted Building III: Six-story RC residential building retrofitted under Plan B

This case involves a six-story RC building, completed in 1991 (Figure 28(a)). The first story is a parking lot, and the second to sixth stories are general residences. This building was retrofitted under Plan B, with a total cost of approximately US$257,800 (including design and supervision) and a work period of 310 days. Shear walls and wing walls were added from the first to the sixth story. The post-retrofit building is shown in Figure 28(b), and the strengthened locations on the structural plan are detailed in Figure 28(c). On-site investigation revealed no significant damage to the main members, as shown in Figure 29.

According to house price registration data on the real estate website (LeWu, 2024c), Retrofitted Building III contains 18 households. Considering without government subsidies, the total retrofitting cost shared by each household is US$14,300. Assuming each household owns 100 m² of usable space, the retrofitting cost per square meter is US$143. Additionally, the average selling price of Retrofitted Building III in recent years was US$1,140/m² (LeWu, 2024c), indicating that the CER of the retrofit project is approximately 8. Notably, the CER of Plan B (e.g., Retrofitted Building III) is much less than the CER of Plan A (e.g., Retrofitted Buildings I and II). Nevertheless, Plan B can more comprehensively protect buildings from earthquakes in comparison with Plan A.

(a)

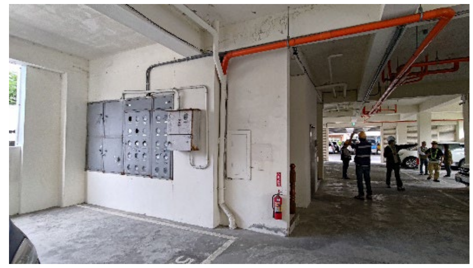
(b)



(c)

Figure 28. Information relating to Retrofitted Building III: (a) before retrofit, (b) after retrofit, (c) structural plan and retrofitted locations (NCREE, 2019).

(a)



(b)

(c)

Figure 29. On-site survey status of Retrofitted Building III after the 0403 Hualien earthquake: (a) exterior, (b) retrofitted with RC walls, (c) retrofitted with wing walls.

5.2 Buildings retrofitted with dampers

5.2.1 Retrofitted Building IV: Six-story hotel (RC building) retrofitted using steel jacketed RC columns and WES-BRBs

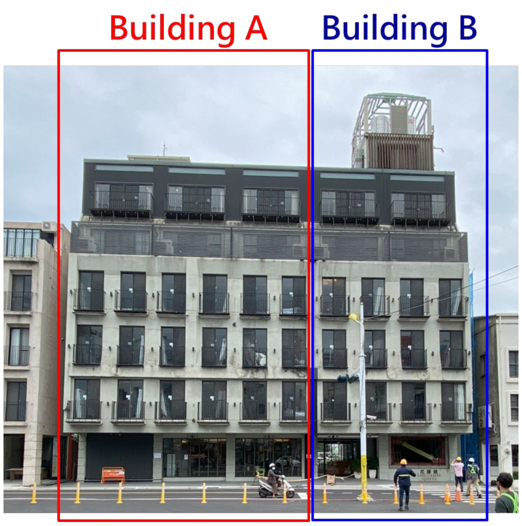
As shown in Figure 30(a), the hotel, located next to a collapsed building that received worldwide attention and was demolished after the 0403 Hualien earthquake, exemplifies the value of seismic retrofitting. The hotel was located at Hualien City and approximately 13 km from the epicenter. Moreover, it is approximately 200 meters from nearby station HWA019. The acceleration response spectra of station HWA019 (Figure 4(a)) suggest that many old buildings, such as the collapsed building, were prone to damage or destruction during the 0403 Hualien earthquake. In comparison, the six-story RC hotel, built at least 52 years ago and retrofitted twice (in 2010 and 2020) to upgrade seismic performance, sustained the earthquake and performed very well.

The hotel consists of two six-story RC buildings (designated as Buildings A and B) with a basement. Buildings A and B were originally constructed in 1969 and 1972, respectively (Figure 31(a)). In 2010, the current building owner strengthened the RC structures using steel-jacketed columns (Figure 31(b)). After the 2018 Hualien earthquake (Lin et al., 2020), the owner foresaw the risk of future earthquakes and decided to further upgrade the seismic performance of the hotel building. A total of twenty welded end-slot buckling restrained braces (WES-BRBs) (Tsai et al., 2014), each with a yield strength of 1,500 kN, were installed in the hotel (Figure 31(b)). Field inspections of the reconnaissance team revealed no obvious damage to the WES-BRBs, gussets, mortar, steel-to-RC interfaces, or RC members, demonstrating the effectiveness of retrofitting using steel-jacketed RC columns and WES-BRBs.

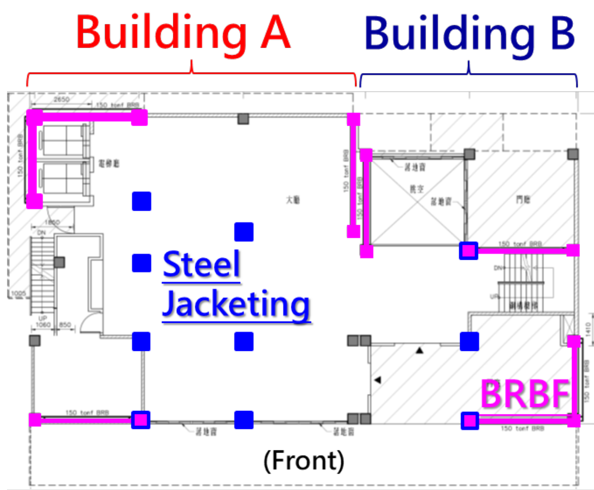
(a)

(b)

Figure 30. Photographs of the retrofitted hotel: (a) next to the collapsed building (taken by a journalist from Taiwan's Central News Agency on April 3, 2024) and (b) front view (taken on May 9, 2024) indicates that the collapsed building had been demolished.



(a)



(b)

(c)

Figure 31. (a) Photograph of the two buildings of the hotel, (b) first-floor framing plan (credit: Mr. An-Chien Wu, NCREE), and (c) BRB frame (photographs taken on May 9, 2024).

5.2.2 Retrofitted Building V: Eight-story bank (RC building) retrofitted using SBRBs

The bank building is an eight-story RC structure with a basement (Figure 32(a)), the building construction completed in 1982. Its floor plan measures approximately 26 m × 21.5 m, with heights of 3.75 m for the first floor and 3.1 m for the second to eighth floors. The RC exterior wall thickness is 12 cm at the rear facade, while the indoor stairs and elevator walls on the same side have 20 cm RC walls. The front facade serves as the entrance facing the road, with fewer walls, leading to noticeable asymmetry in the overall structure. The structural retrofit of this building was completed in early 2024, before the 0403 Hualien earthquake. Because the interior continued to be used as a bank during the retrofit period, the methods and locations of the retrofit differed from those of conventional RC retrofitting. The retrofit involved installing all-steel Sandwiched Buckling-Restrained Braces (SBRBs) (Chou et al., 2010; Chou et al., 2024) and thickening existing walls with 20 cm RC walls from the basement to the fifth floor. A total of 25 sections of 20 cm RC walls and 52 sets of all-steel SBRBs were added (Figure 32(b) and (c)). The SBRB was composed of a steel core plate, sandwiched by a pair of restraining members without concrete infill. The SBRB retrofit method entails adding a steel boundary frame within the existing RC frame, including the steel top and bottom beams and columns on both sides (Figure 32(d)) The boundary frame are chemically anchored to the existing RC structure, while thickening the RC walls also reinforces the surrounding beam and column sections. Retrofit locations were selected around the perimeter of the building to provide structural strength and promote symmetry in the structural system, thus reducing torsional effects (Figure 32(e)). During the site inspection (Figure 32(f)), the building exhibited no damage, and no structural cracks were observed in the retrofit building after the 0403 Hualien earthquake. At the SBRB on the first floor, the debonding material was slightly deformed, leading to minor paint peeling on the outer layer (Figure 32(g)). This indicates the SBRB deformation during the earthquake, although the deformation was not substantial.

SBRBs are effective seismic energy dissipation components, comprising a core steel plate and surrounding restraining members (Figure 32(h) and (i)) (Chou et al., 2010; Chou et al., 2024). The restraining members consist of upper and lower units welded from steel plates and steel channels, bolted on both sides of the weak axis of the core plate. Its all-steel construction facilitates quick manufacturing and installation, with stable seismic performance. It has already been used in several newly constructed high-rise buildings. The eight-story bank building is the first building to be retrofitted using all-steel SBRBs. This building is approximately 250 meters from the collapsed building (Figure 30(a)) and has a similar height. Additionally, it was constructed before the collapsed building. Based on the results of on-site microtremor measurements and covariance-driven stochastic subspace identification (SSI-COV) analysis, the building's period was 0.36 s. Comparing this with the response spectrum recorded from the nearest station (HWA019, approximately 200 meters away) (Figure 4(a)), the corresponding maximum acceleration in the north-south direction was 1 g. Although the ground motion had a very high acceleration demand on the retrofitted building, the retrofitted bank building performed very well during the 0403 Hualien earthquake, demonstrating the effectiveness of the retrofit using all-steel SBRBs and thickened walls.

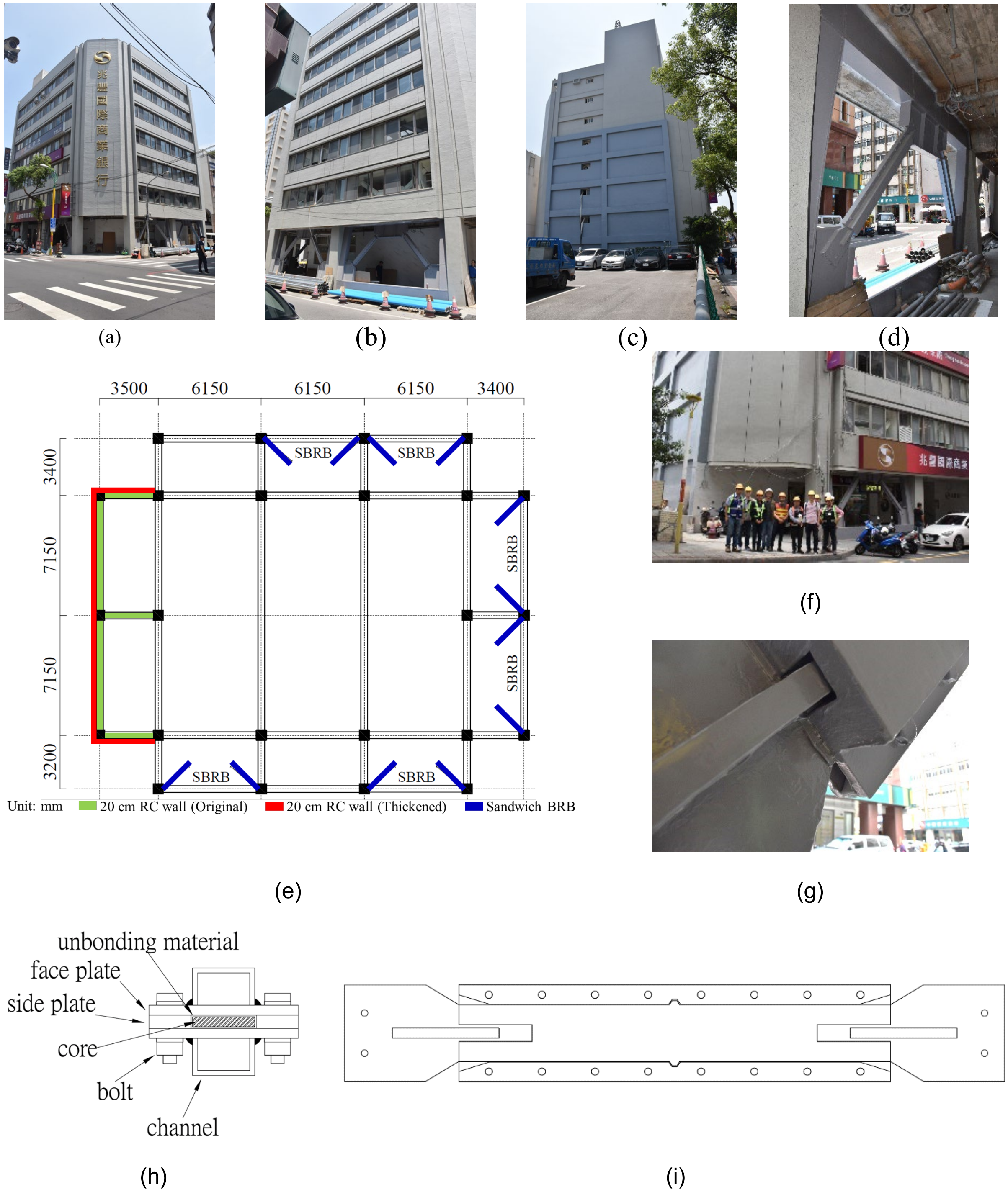


Figure 32. Eight-story bank building: (a) overall view, (b) retrofitting with SBRBs, (c) retrofitting with RC wall, (d) added steel frame and SBRB, (e) plan drawing, (f) reconnaissance team member and building, (g) deformation track, (h) SBRB cross section, (i) SBRB lateral view.

5.3 Base-isolated Buildings

During the earthquake inspection, two base-isolated buildings were visited, an eleven-story hospital and a seven-story office building. The eleven-story hospital was a steel-reinforced concrete (SRC) structure with eleven floors and two basement levels (Figure 33(a)). The isolation floor was located on the second base floor (B2F). The eleven-story hospital was situated 3 km from the Hualien city center. The maximum horizontal ground acceleration measured at the B2F of this building was 205 gal, less than half of the 500 gal recorded in Hualien city center.

This building was equipped with 88 lead rubber bearings (LRBs) of various shapes and sizes (Figure 33(b)). Displacement records of the lead pendulums adjacent to the LRBs in the B2F isolation floor after the earthquake indicated significant residual displacement. Direct inspection of the LRBs also revealed noticeable residual deformation (Figure 33(c)). On-site measurements revealed that the earthquake caused a displacement of approximately 300 mm in the isolation floor in the long direction of the building and about 400 mm in the short direction.

Despite causing significant deformation and residual displacement of the isolation devices, the earthquake did not result in structural damage to the building. However, it did cause damage to some non-structural elements. Figure 33(d) illustrates the relative position of the first-floor isolation structure and the ground. Because of insufficient clear space, the isolation floor displacement during the earthquake led to compression against the exterior ground structures. This resulted in observable damage, such as cracked concrete pedestals in the flower beds and sidewalks (Figure 33(e)). Additionally, during the earthquake the driveway cover plates (Figure 33(f)) were compressed and deformed, but they were repaired shortly after the event.

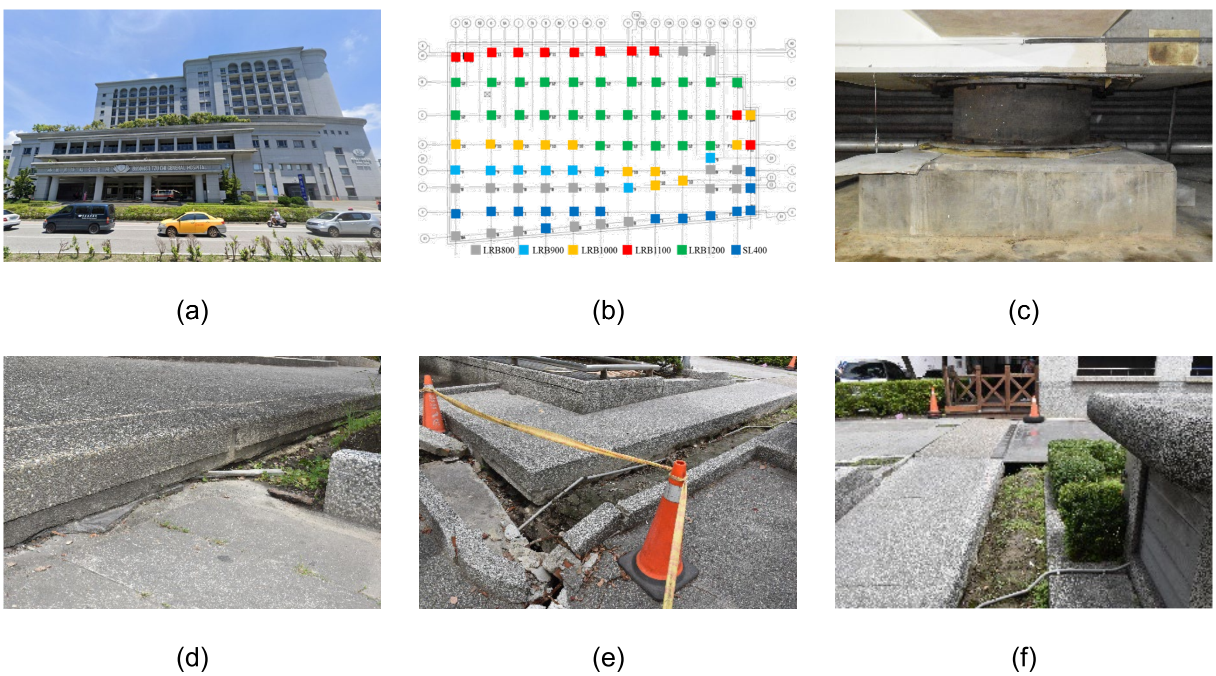


Figure 33. Photographs and figures of the eleven-story hospital: (a) overall view (credit: Google Maps), (b) LRB layout, (c) LRB, (d) gap between isolation floor and ground, (e) damaged non-structural elements, (f) repaired driveway cover plates.

The second base-isolated building was a structure with seven floors and two basement levels (Figure 34(a)), constructed using SRC. The isolation floor was located between the first base floor (B1F) and the ground level (1F), with a total of 36 LRBs installed. This building is an instrumented structure. To record structural behavior, measuring instruments were installed at the center and corners of the isolation floor. These instruments included bi-directional displacement meters and triaxial accelerometers to measure displacement in the isolation layer and acceleration in the superstructure (Figure 34(b)).

Because of the structural behavior of the isolated building, there was a possibility that significant displacement would occur at the isolation floor. Therefore, all pipelines passing through the isolation floor were connected using flexible hoses to accommodate deformation (Figure 34(c)), while those not passing through the isolation floor were fixed as in a typical structure. During the 0403 Hualien earthquake, the entire building, including the isolation devices and the SRC structure, did not undergo any structural damage. A site inspection of the connections between the isolation floor and the ground revealed no non-structural damage due to enough space reservation (800 mm) and well-configured sliding devices.

Because the field reconnaissance coincided with a comprehensive inspection of the isolation devices arranged by the owner following the 0403 Hualien earthquake, the LRB devices were observed directly (Figure 34(d)). No significant residual deformation was visible to the naked eye. Annual inspection records are maintained for each LRB (Figure 34(e)). For the LRB supports located near the exterior, simple displacement measurement tools such as laser rangefinders enabled direct measurement of the distance between the superstructure and the retaining wall. These measurements were recorded during the inspection of the structure, and the records indicated almost no residual displacement (Figure 34(f)). The B1F below the isolation floor served as a parking lot. Floor openings were reserved between the isolation floor and the parking lot, facilitating quick transportation if the LRBs required replacement (Figure 34(g)).

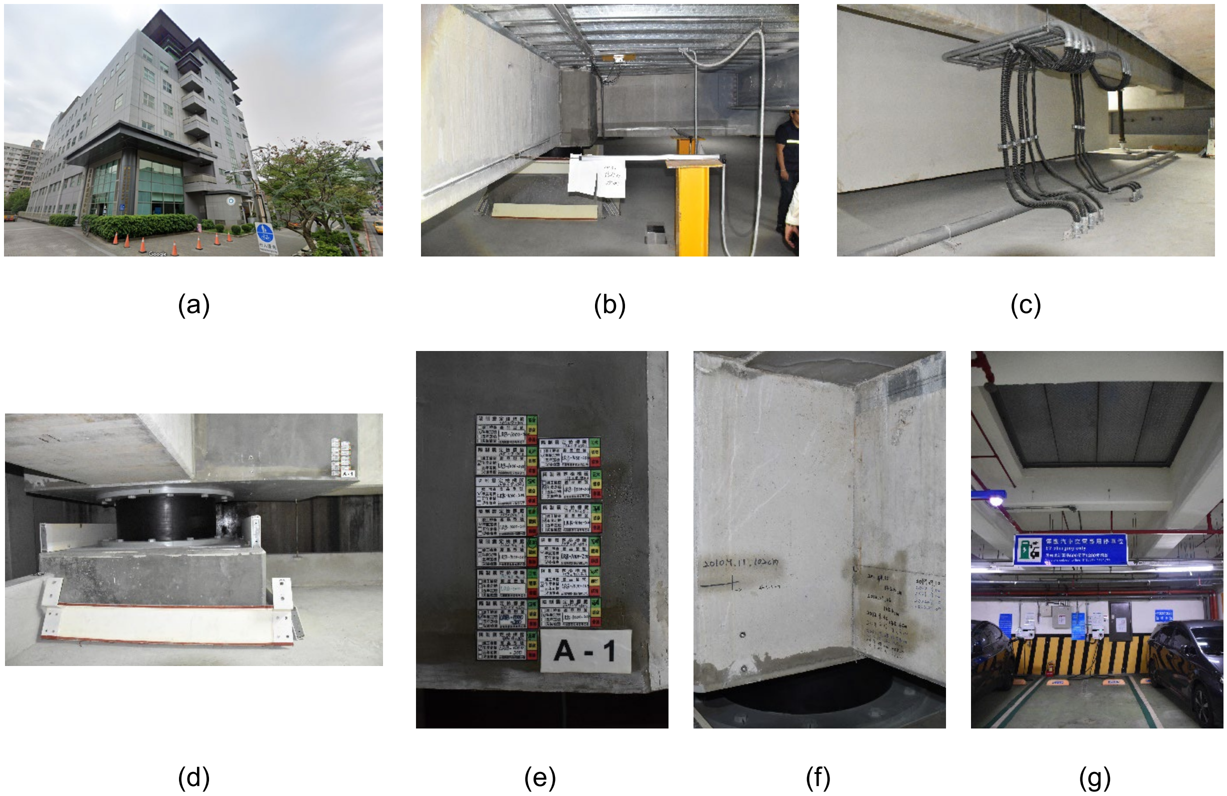


Figure 34. Photographs of the seven-story office building: (a) overall view (credit: Google Maps), (b) measuring instruments, (c) flexible hoses, (d) LRB, (e) annual inspection records, (f) measured record, (g) floor opening for LRB repair.

6 PRE-EARTHQUAKE PREPAREDNESS

Given that the magnitude of 0403 Hualien earthquake is similar to that of the 1999 Chi-Chi earthquake, it is worth exploring the factors leading to their very different consequences. The measures taken in Taiwan for seismic preparedness during the 25 years following the 1999 Chi-Chi earthquake are highlighted.

6.1 Seismic demand

From the perspective of seismic demand, the 1999 Chi-Chi earthquake, with its hypocenter 8 km beneath central Taiwan, caused seismic intensities in seven counties to reach the then-highest intensity level 7 (i.e., PGA greater than 400 gal). In contrast, the intensity levels caused by the 0403 Hualien earthquake, which occurred near offshore east of Taiwan with a focal depth of 22.5 km, were 6+ in Hualien County, 6- in Hualien City, 5+ in Yilan County and Miaoli County, and 5- in seven other counties. Taiwan implemented new seismic intensity levels on January 1, 2020, and the old and new seismic intensity levels are compared in Table 1. The data in Table 1 indicate that the current intensity level greater than level 4 is determined by PGV rather than PGA. According to the PGA map of the Hualien earthquake, only Hualien County, Hualien City, and Yilan County reached the old intensity level 7. Therefore, the seismic loss due to the Hualien event was naturally much less than that from the 1999 Chi-Chi earthquake. Nevertheless, the Hualien seismic event, which resulted in only two collapsed buildings and 18 fatalities (most of which were caused by landslides and rockfalls, with one fatality from a collapsed building), still aroused global interest about how and why Taiwan was able to withstand a major earthquake so well.

Table 1. Old and new intensity levels adopted in Taiwan (CWA, 2023).

Old	Intensity level	0	1	2	3	4	5		6		7
	PGA (cm/s^2)		0.8	2.5	8.0	25	80		250		400
New (2020/1/1)	Intensity level	0	1	2	3	4	5-	5+	6-	6+	7
	PGA (cm/s^2)		0.8	2.5	8.0	25	80				
	PGV (cm/s)						15	30	50	80	140

6.2 Updated building seismic design code

Following the 1999 Chi-Chi earthquake, Taiwan substantially increased the minimum seismic base shear force for buildings. For buildings approximately 50 or 40 years old, the minimum seismic base shear force (denoted as V) was calculated as V = ZKCW and V = ZKCIW, respectively, according to the TBTR of 1974 and 1982. Factors Z, K, C, and W account for seismic zonation, structural ductility, seismic coefficient, and building weight, respectively. The building importance factor I was first introduced in the TBTR 1982. The factor C was further revised in the TBTR 1989 to consider the Taipei Basin effect. In 1997, the TBSDC was initiated. The articles regarding the minimum seismic base shear force for buildings were transferred from TBTR to TBSDC, separating seismic design from architectural regulations. TBSDC 1997 stipulated V as follows:

$$V = \frac{ZI}{1.4\alpha_y}\left(\frac{C}{F_u}\right)_m W \tag{1}$$

where Z is the seismic zone factor, I is the building importance factor, C is a normalized lateral spectral acceleration coefficient, α_y is a seismic force amplification factor at the yielding point, and F_u is a seismic force reduction factor according to the ductility of the structural system. TBSDC 1999 adjusted the seismic zone factor Z immediately after the 1999 Chi-Chi earthquake. TBSDC 2005 refined the seismic zonation map based on town boundaries (i.e., micro-zonation) and considered the near-fault effect. In addition to the design response spectra for DBEs, the design response spectra for MCEs were first introduced in TBSDC 2005. TBSDC 2011 retained the computation of V used in TBSDC 2005, but the factor α_y was changed from 1.5 to 1.0 for RC structures using the ultimate strength design. Because the corresponding loading factor was modified, the applied seismic force based on TBSDC 2011 remained unchanged compared with that based on TBSDC 2005. The latest version of TBSDC was enacted in 2022. TBSDC 2022 retained the computation of V used in TBSDC 2011 but revised the near-fault effect, taking into consideration recently identified faults. Moreover, considering the severe casualties resulting from the collapse of buildings with weak and/or soft stories during past seismic events in Taiwan (Lin et al., 2020), TBSDC 2022 first promoted the seismic retrofitting of weak stories in cases where complete seismic retrofitting of a whole building is not achievable. Figure 4(a) shows the response spectra obtained from the ground accelerations recorded at the strong ground motion station HWA019 compared with the design response spectra of TBSDC 2022 and TBSDC 1997. The minimum seismic base shear force stipulated in TBTR 1989 is also illustrated. Figure 4(a) indicates that the design response spectra of TBSDC 2022, like those of TBSDC 2005 and TBSDC 2011, exhibited considerably higher intensity than that of TBSDC 1997. According to the evolution of relevant building regulations and codes in Taiwan, the 1999 Chi-Chi earthquake was a watershed for the design base shear of buildings. As a result, the seismic capacities of buildings constructed after the 1999 Chi-Chi earthquake are generally higher than those built before. For buildings older than 40 years, deterioration of structural materials is likely an additional factor contributing to insufficient seismic capacities.

6.3 Enforcing seismic retrofitting of school buildings and public buildings

After the 1999 Chi-Chi earthquake, the seismic capacities of buildings in Taiwan were enhanced by increasing the seismic design force stipulated in the TBSDC and by conducting nationwide seismic retrofitting projects. During the 1999 Chi-Chi earthquake, nearly half of the school buildings in central Taiwan collapsed or were severely damaged. Hence, Taiwan's NCREE conducted numerous experiments on components and frames of school buildings in laboratories and on-site from 1999 to 2009. Based on the experimental results, seismic evaluation and retrofitting methods for school buildings were gradually developed. In 2009, Taiwan's Ministry of Education (MOE) launched a nationwide project for the seismic evaluation and retrofitting of school buildings. Under the MOE's supervision, and with administrative and financial support, the NCREE was commissioned to conduct the nationwide project from 2009 to 2022. Consequently, a total of 10,163 out of 27,227 school buildings were seismically retrofitted, averaging 782 retrofitted school buildings per year. To minimize the disruption to teaching and learning activities, seismic retrofitting work was largely conducted during summer and winter vacations. Common retrofitting methods included adding shear walls and wing walls and enlarging column cross-sections. The total budget for the nationwide project was US$4 billion. The performance of retrofitted school buildings was satisfactorily verified during the 0403 Hualien earthquake, as well as previous seismic events (Lin et al., 2020) In addition to school buildings, seismic retrofitting is compulsory for public buildings such as public hospitals, police and fire department buildings, and public markets. The seismic retrofitting of public buildings in Taiwan began in 2000. As of 2017, over 5,000 public buildings had been seismically retrofitted. On average, the cost of retrofitting a building is approximately 11% of the cost of demolishing the old building and constructing a new one.

6.4 Promoting seismic retrofitting of private buildings

Besides enforcing the seismic retrofitting of public buildings, the Ministry of the Interior (MOI) issued a subsidy policy in 2019 to encourage the retrofitting of private buildings, such as apartments and mixed-use buildings. The subsidy policy refunds 85% of the retrofitting fee, up to NT$4.5 million (approximately US$150,000) per building. Moreover, owners can choose their retrofitting targets, either retrofitting only weak stories or ensuring at least 80% of the seismic capacity stipulated in TBSDC 2011. This means that partial retrofitting of a building is acceptable. Since 2019, the NCREE has assisted the MOI in promoting and implementing the policy. Due to the challenges in reaching a consensus among building owners, only 80 cases have been approved so far, with 22 completed. Notably, all privately retrofitted buildings performed well during the Hualien seismic event.

6.5 Other efforts for reducing seismic vulnerability in Taiwan

Public awareness of seismic threats increased significantly after the 1999 Chi-Chi earthquake. Since 2000, September 21 has been designated as National Disaster Prevention Day in Taiwan. On this day, the National Fire Agency of the MOI collaborates with public and private organizations to conduct emergency response drills. Additionally, Taiwan has established a public warning system. In the event of an earthquake with a magnitude exceeding 5.0, individuals in areas predicted to experience seismic intensities greater than level 4 receive earthquake alerts from the CWA. A clear demonstration of heightened public awareness was observed during the field reconnaissance following the 0403 Hualien earthquake: individuals had spontaneously enlarged the cross-sections of outdoor columns in undamaged street buildings. Although these non-engineered retrofitting efforts were flawed (e.g., using stirrups without hooks), they are expected to improve the seismic performance of the buildings to some extent. On the other hand, corrupt construction practices were curbed as far as possible. For instance, five individuals responsible for the design or construction of a 16-story mixed-use street building from 1992 to 1995 that collapsed during a seismic event on February 6, 2016 in southern Taiwan, were given jail sentences. Such legal action and similar cases play a crucial role in deterring poor construction quality. Despite government subsidies and voluntary efforts to retrofit private buildings, the number retrofitted remains insufficient. The NCREE continues to advocate comprehensive legislation to enforce the enhancement of seismic resistance in existing buildings, especially those constructed before 1999.

7 SUMMARY AND CONCLUSIONS

The casualties and collapsed buildings caused by the 1999 Chi-Chi earthquake and 2018 Hualien earthquake deepened people's awareness of the importance of seismic preparation and contingency response. The 0403 Hualien earthquake (M_L 7.2) stands as the strongest earthquake in Taiwan since the 1999 Chi-Chi earthquake (M_L 7.3). The amplified spectral accelerations at the periods shorter than 1.3 s implies that many existing buildings constructed before 1999 may be prone to be damaged. Fortunately, the inspected buildings that were retrofitted using common techniques or novel dampers revealed no obvious damage or kept intact, and thereby demonstrating the effectiveness of retrofitting.

Based on the post-earthquake filed reconnaissance in cities and towns near the epicenter, the report aims at sharing the knowledge gained to provide insight into how structures performed under such conditions and to highlight lessons that might improve current design practices in earthquake-prone areas. The observations and learning are summarized as follows:

1. Structural damage occurred in pre-Chi Chi buildings, while no significant affectations were observed in modern structures. That means that the preparedness of the country in the last decades has paid off.
2. Reinforced concrete frames were the most used structural systems for buildings in the affected areas. Most of the buildings had infill walls with solid clay bricks.
3. The damage occurred due to a combination of factors, including the large magnitude of the earthquake, age of the buildings, and construction practices before 1999, *i.e.,* lack of RC components, poor detailing, and others. These factors led to insufficient ductile behavior of elements or connections, resulting in the observed affectations. In addition, illegal remodeling of indoor spaces, and adding top stories were possible reasons for the severe damage observed in the field inspection.
4. The common identified mistakes in damaged RC buildings were: i) inadequate quantity and distribution of transverse ties; ii) incorrect spacing and formation of 135-degree hooks for stirrups; iii) poor quality concrete, including the use of river rocks as aggregate and sea sand, leading to inadequate behavior of structural elements.
5. The mix-used building complex in Nanjichang Night Market is more than 60 years old. The issue of seismic retrofitting of such old buildings should be considered along with durability, landscape, and urban planning.
6. The severe damaged street buildings indicate that the exterior columns of corridors appeared to be common structural weak points in this type of building. Strengthening corridor columns (e.g., through column jacketing) or adding braces along the exterior of the corridors could potentially serve as effective seismic retrofitting measures for such street buildings.
7. The cracked brick walls surrounding the staircases of the inspected street buildings indicate that these walls played a significant role in resisting the earthquake load. Although brick walls are generally disregarded in structural design of buildings in Taiwan, their role should be carefully considered for realizing safe and economical building design.
8. The most common failure mechanism was the soft-story collapse of the first or two stories, which was related to the inappropriate behavior of vertically RC elements. The proportion of multi-story collapse was more significant in areas of higher shaking. It is urgent to identify and retrofit the buildings prone to collapse due to seismic soft or weak stories.
9. The significant downtime and financial losses of the National Dong Hwa University highlighted the need of developing the approach of preventing compound disaster and the technology of earthquake-resistant non-structural components.
10. The seismic performance of the retrofitted buildings, which adopted common retrofitting techniques (*e.g.,* added RC wall) or novel devices (*e.g.,* BRB), was satisfactorily verified. In addition, the short work period and high cost-effectiveness ratio from applying common retrofitting techniques to the three residential buildings are remarkable.
11. The 1999 Chi-Chi earthquake stimulated the evolution of Taiwan Building Seismic Design Code, which raised the seismic capacities of buildings constructed after the 1999 Chi-Chi earthquake. Considering many of the buildings with severe damages being constructed before the 1999 Chi-Chi earthquake, the modern and proper building seismic design codes are critical for the pre-earthquake preparedness.
12. The Taiwan government conducted a nationwide project for the seismic evaluation and retrofitting of school buildings and public buildings after the 1999 Chi-Chi earthquake. Considering the satisfactory performance of the retrofitted school buildings and public buildings during the 0403 Hualien earthquake, it is worth further conducting comprehensive seismic evaluation and retrofitting of private buildings.

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