Bulletin of the New Zealand Society for Earthquake Engineering, Vol. 59, No. 2, June 2026

FUNCTIONAL RECOVERY OF BUILDINGS FOR SEISMIC RESILIENCE OF COMMUNITIES: LESSONS FROM THE 2024 HUALIEN, TAIWAN EARTHQUAKE

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(Submitted *June 2025*; Reviewed *September 2025*; Accepted *February 2026*)

ABSTRACT

Functional recovery is a new design strategy in earthquake engineering that prioritises rapid recovery and building re-use after severe natural disasters. It suggests holistic building performance goals focused on structural robustness, enhanced safety, and a rapid return to operations post-event. To paint a realistic picture of post-earthquake building recovery trajectories, there remains a significant gap in knowledge for calibrating existing building seismic performance assessment frameworks using empirical data from earthquakes. The 2024 Hualien Earthquake in Taiwan provides a unique opportunity to calibrate this approach and improve our understanding of building seismic performance and how the functional recovery of buildings affects community resilience. A reconnaissance trip was undertaken in Hualien, and damage data from 16 buildings were collected to generate functional recovery lessons and benchmark the FEMA-P58 framework using SP3 software. The research suggests that the closure or limited use of some residential buildings was largely due to extensive damage to non-structural elements, including egress and elevators, ceilings, partitions, facades, and glazing. Business disruptions were mainly caused by restricted access or cordons put in place for the safe demolition of adjacent buildings. The adaptive resilience and preparedness of building owners, residents, and businesses appeared to play a significant role in the re-use of buildings. The functional recovery data and lessons learned from Hualien, particularly the positive outcomes of its building retrofit programmes, would support the ongoing development of low-damage design guidelines and seismic design practice in New Zealand that can enhance the seismic performance and recovery of buildings.

https://doi.org/10.5459/bnzsee.1760

INTRODUCTION

Recent earthquakes, such as the 2010/2011 Canterbury Earthquake sequence and the 2016 Kaikōura Earthquake in New Zealand (NZ), have clearly demonstrated that buildings designed to code requirements performed well from a life-safety perspective. Nevertheless, these events have also highlighted the impact of significant economic and social disruptions on communities due to the loss of building functionality and the cost of repairs after an earthquake [1,2]. In several countries, including the United States of America (USA) and NZ, seismic design is undergoing fundamental change. Policymakers (e.g., Federal Emergency Management Agency (FEMA) [3] and Ministry of Business, Innovation and Employment (MBIE) [4]) and engineers (e.g., Stanway et al. [5]; Earthquake Engineering Research Institute (EERI) [6] and QuakeCoRE [7]) have been calling for 'above code' practice regarding building codes and standards, not only to focus on protecting life safety, but also to prevent loss of functionality and minimise disruptions.

To reduce the disruptions associated with loss of use and the repairs needed to resume functions, building downtime must be considered. Functional recovery, a philosophical shift in design strategy, has been introduced in earthquake engineering that prioritises rapid recovery and building re-occupancy after severe natural disasters [6]. It suggests holistic building performance goals, focused on structural robustness, enhanced safety, and specifically, damage control to ensure a rapid return to operation [7]. Based on these performance objectives, engineers need robust seismic performance estimation models to provide confidence that changes to designs and prescriptive requirements achieve the performance required to meet functional recovery targets. In New Zealand, this above code practice is currently being developed in detail and introduced as practice guidelines by MBIE as the Low Damage Seismic Design Guidelines [4].

The general methodology for seismic performance assessment encompasses various yet consistent approaches. FEMA P-58 [3] was developed to assess the seismic performance of individual buildings, quantified through metrics such as repair costs, casualties, repair time, placarding, and environmental

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impacts. Arup's Resilience-Based Earthquake Design Initiative (REDi) builds on and extends beyond FEMA P-58 [8]. REDi enables a comprehensive assessment of building downtime across different functionality states and explicitly considers the impact of utility disruptions and impeding factors such as permitting, inspections, financing, and engineer or contractor mobilisation in the modelling process. Additionally, drawing on the workflow of FEMA P-58, Applied Technology Council's (ATC) ATC-138 [9], establishes re-occupancy and building function modules to estimate the loss of building function and recovery time. The quantification of the effects of impeding factors suggested by REDi is also incorporated into ATC-138 when assessing building recovery time.

A systematic review of functional recovery studies and frameworks by Li et al. (2023) summarised these pioneering methodologies (FEMA P-58, REDi, and ATC-138) as well as advanced frameworks or approaches developed by several researchers [10]. It is important to note that the concept of assessing and designing structures based on performance objectives is not new. It originates from the Performance-Based Earthquake Engineering methodology [11-13], which served as a pivotal foundation for the subsequent development of FEMA P-58 and REDi guidelines.

For design criteria to be effective, the correlation between damage and post-earthquake functionality state needs to be calibrated against the performance of structures in earthquakes. The Mw 7.4 earthquake that struck off the coast of Hualien, on Taiwan's east coast, on April 3, 2024, provided a unique opportunity to collect data on functional recovery of buildings, such as damage, losses, disruptions, and impeding factors (e.g., utility disruptions), and calibrate end-to-end building-level predictions of performance by using FEMA P-58. The reporting on limited building damage further warranted a reconnaissance trip to learn lessons on functional recovery.

This work aims to contribute to the field of functional recovery for seismic resilience by: (1) investigating correlations between building damage and its functionality post-earthquake; (2) demonstrating how different building elements and impeding factors contextually affected the functional state of individual buildings; and (3) suggesting the conditions for effectively using FEMA P-58 methodology when assessing building seismic performance.

LITERATURE REVIEW

Many studies have proposed approaches to improving the estimation of post-earthquake building losses and the time required to restore building functionality, whether through building archetype-based loss estimation models such as HAZUS [14]; the Assembly-Based Vulnerability framework [15]; catastrophe models (Cat models) [16]; or facility component-based models such as FEMA P-58 [3], REDi [8], and ATC-138 [9]. The common rationale is to estimate losses and downtime using fragility functions that quantify the probability of damage to structural and non-structural components.

Using a probabilistic approach, FEMA P-58 defines a four-step process to estimate a building's performance by sequentially analysing hazard, structural, damage, and loss characteristics. Tools such as the Performance Assessment Calculation Tool (PACT) are commonly used to calculate damage and losses. PACT draws on a library of fragility curves to estimate the probability of damage to structural and non-structural components and to estimate the time required to restore functionality [17]. FEMA P-58 does not include a dedicated module for calculating functionality. Nonetheless, both damage and loss estimates can be used in sequential analyses to determine functional loss.

Several attempts have been made to develop advanced functional recovery models to simulate the entire building recovery process and estimate the time for building re-occupancy and re-use [18-21]. In particular, efforts have been made to quantify the impact of impediments, such as resource scheduling [18], human constraints [20], and safety cordons [21], on the recovery trajectories of buildings. Existing benchmarking studies of previous earthquakes, like the 2010/11 Canterbury Earthquake sequence [22-23], 2009 L'Aquila Earthquake [24] and 1994 Northridge Earthquake [25], and functional recovery reconnaissance efforts from the 2023 Turkey-Syria Earthquakes [26] have highlighted the importance of quantifying functional recovery targets for individual buildings, taking into consideration ground motion, building response, damage to both structural and non-structural components, and other relevant factors.

According to FEMA P-2090/NIST (National Institute of Standards and Technology) SP-1254 [27], a key concept for the functional recovery of buildings is to maintain the basic intended functions associated with the building's pre-earthquake use or occupancy. Together with re-occupancy, functional recovery is a post-disaster performance state for which recovery-based objectives can be defined at specified levels of earthquake shaking within performance-based seismic design. Globally, recovery-based design objectives have not been included in current building codes. However, such design practices or codification processes, moving from life-safety to functional recovery (or low-damage design), have been implemented in high-seismic-risk countries such as the USA and NZ. Recent initiatives such as FEMA's National Earthquake Hazards Reduction Program (NEHRP) Committee Functional Recovery Task Committee in the USA and Seismic Risk Working Group in NZ, as well as guidance documents such as FEMA's P-2090/NIST SP-1254 [27] and NZ's Low Damage Seismic Design resources [4], provide guidance that may in time be included in standards, likely requiring explicit consideration of design objectives for re-occupancy and functional recovery.

Despite recent advances in recovery-based design and computational capabilities for assessing seismic building performance, there remain unaddressed issues concerning the need to improve the quantitative and qualitative understanding of event-specific building damage, its correlation with re-occupancy and functional recovery performance state and some aspects of resilience that might contribute to achieving or maintaining functional recovery following an earthquake [28,29]. This research, based on extensive data collection undertaken as part of reconnaissance to Hualien, Taiwan, will lead to an improved understanding of building design and decision making for functional recovery from both engineering and community resilience perspectives.

BACKGROUND: HUALIEN EARTHQUAKE AND BUILDING DAMAGE

The 2024 Hualien Earthquake (Mw 7.4), with its epicentre located approximately 25 km east of Hualien City, was the strongest seismic event in Taiwan since 1999. The earthquake caused widespread intense ground motions across the country, particularly in Hualien, where peak ground accelerations exceeded design-level demands for many structures. Despite the collapse of six buildings (four during the mainshock of April 3 and the other two during the aftershocks on April 23) and extensive structural and non-structural damage, the casualty rate remained low. According to field investigations, older and non-retrofitted buildings, especially those with masonry infill walls and corner or irregular configurations, were particularly vulnerable. Commonly observed damage included shear failure, concrete spalling, inadequately detailed lap splice failure in plastic hinge zones, and out-of-plane failure of partition walls. In contrast, newer or retrofitted buildings demonstrated satisfactory seismic performance, with little or no damage observed, indicating the effectiveness of the retrofit initiatives in Taiwan and contemporary design codes. Notably, the buildings that collapsed in this event were those with prior damage in past events that reduced their as-built structural capacity but had not undergone adequate seismic upgrades.

In response to the earthquake, the local government promptly initiated a coordinated post-event assessment of building damage. Trained civil and structural engineers and architects conducted on-site inspections and issued placards indicating building safety: red placards indicated buildings unsafe to enter, yellow placards allowed limited access (e.g., for belongings retrieval), and no placard signified a green rating (e.g., buildings could be used). For buildings that had no placards, a green placard has been assigned for the purpose of this paper. The National Centre for Research on Earthquake Engineering (NCREE) of the National Institute of Applied Research (NIAR) played a critical role in organising inspections and facilitating data collection. NCREE also contributed to refining indices for evaluating building safety and coordinated placarding updates after major aftershocks.

RECONNAISAINCE DATA COLLECTION

The detailed reconnaissance efforts conducted in Hualien, Taiwan, by the New Zealand Society for Earthquake Engineering (NZSEE) Learning from Earthquakes (LFE) team are presented in an article by Lee et al. (2025) [30]. Two teams (A and B) were deployed at different times following the Hualien Earthquake. While Team A (deployed from May 7–14) focused on inspections of structural damage and performance of retrofitted buildings, Team B (deployed from May 29–June 6) took a holistic approach to learning general lessons from building and infrastructure damage, recovery governance, and disaster risk reduction in Taiwan. One of Team B's primary reconnaissance goals was to collect functional recovery data from a range of buildings affected by the earthquake.

Figure 1: Location of visited structures with their placard colours assigned. Source: https://www.google.com/maps/d/edit?mid=1l7ZoeuFRp2Vom1TBSMHRqrk6NHx2ENc&usp=sharing

Similar to the functional recovery questionnaire developed by EERI's Housner Fellows, the functional recovery data collection tool devised in this study also recorded data on factors affecting functionality, in addition to structural damage data following the Rapid Building Damage Assessment Guide used in NZ [31]. The survey collected building damage data and associated functional losses; external factors affecting the building's functionality; data on utility disruptions; disruptions to organisations or individual residents occupying those buildings; and decision-making factors such as impediments to recovery. Survey questions were entered into the ArcGIS Survey123 to facilitate data collection. Where possible, the team gathered data by speaking with building managers, building owners, and local residents to develop a full account of what had happened to each building in terms of functional loss.

Team B had the opportunity to collect data on the functionality and functional recovery of 16 buildings in Hualien (see Figure 1). As shown in Figure 2, by building type, there were six multi-storey residential apartment buildings, five commercial buildings, and five mixed-use buildings combining commercial and residential uses.

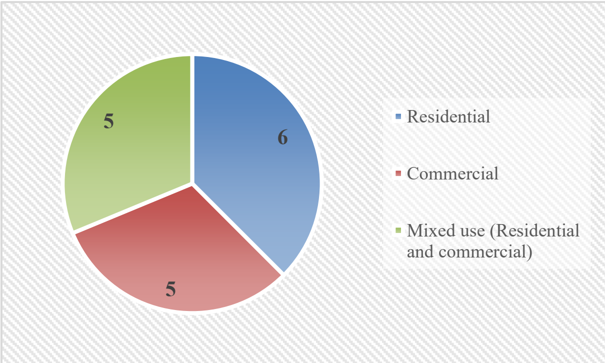

Figure 2: Types of buildings visited.

Construction eras for the 16 buildings are shown in Figure 3. Three buildings were built in the 1960s, two in the 1970s, 10 were constructed during the boom period before the 1999 Chi-Chi Earthquake, and one was built in 2015.

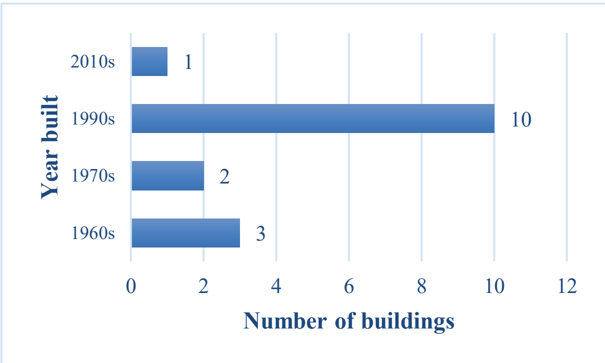

Figure 3: Construction age of buildings visited.

As shown in Table 1, the six retrofitted buildings generally performed well during the earthquake, with only one old building (D10, built in 1968) assigned a yellow placard. Ten buildings that had not been retrofitted performed poorly, with six buildings red-placarded and three yellow-placarded. One building complex (E11), comprising six buildings (A–F), all suffered varying degrees of damage, with buildings A and F allocated red placards and the other four buildings assigned yellow placards. The inspection of this building complex, E11, was focused on Buildings A and F; thus, a red placard was issued for this complex in Table 1 and Figure 4 below. This building complex had a prolonged construction period: beginning in 1991 and completed in 1998, with construction suspended several times due to legal disputes between the developer and the bank. Another building (A03) was assigned a yellow placard after the main shock and later received a red placard after the subsequent aftershocks.

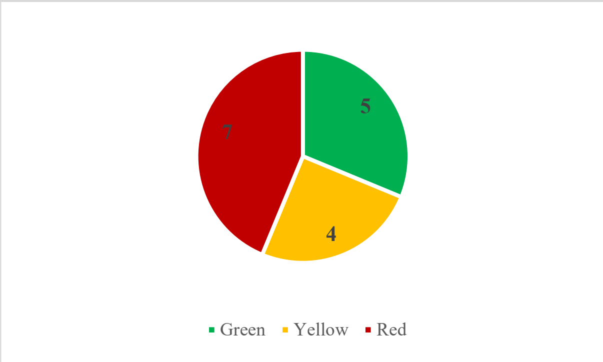

Figure 4: Placards of buildings visited (as of time of visit in May–June 2025).

It is worth highlighting that seismic building performance assessment using FEMA P-58 requires substantial data inputs at the building component level. Although Team B visited 19 buildings (18 in Hualien and one in Taipei) for functional recovery data collection, only 16 buildings have complete data sets from both Team A and Team B. Therefore, the results presented below, including general observations on types of damage associated with building functionality loss and the FEMA P58 benchmarking analysis, were undertaken using 16 selected buildings.

BENCHMARK METHODOLOGY

SP3 software [32] was used to predict the seismic performance of buildings following the 2024 Hualien Earthquake scenario. SP3 uses the FEMA P-58 [3] and ATC-138 [9,25] frameworks. FEMA P-58 performance predictions using SP3 were then benchmarked against observed building performance data in Hualien. Such a comparison can provide insights into the robustness and applicability of FEMA P-58 seismic risk and recovery assessment guidelines, methodologies, and assumptions to different regions and events. In particular, the comparison metrics will also reveal the underlying factors contributing to damage or to functional recovery, beyond the scope of FEMA P-58 assessment.

Table 1 summarises the 16 buildings selected for this study. The methodology applied for the FEMA P-58 benchmark exercise is shown in Figure 5. The input data for the SP3 software loss estimation included building characteristics and the ground motion at each building location. Reconnaissance data from both Teams A and B were used, including building construction year, building type and lateral system, structural drawings (plans and elevations), occupancy type, number of storeys, floor area, past retrofits, irregularities, significant construction flaws, and details about building components. Records also included whether the building was occupied and/or functional at the time of the visit, and whether it appeared repairable. Furthermore, the experienced seismic demand at each building location, in terms of peak ground acceleration (PGA), was extracted from the NCREE hazard maps [33] produced for the main event. Qualitative data collected from building managers, owners, and tenants, where opportunity allowed, included disruptions that occurred, whether the building had experienced disruptions to utility services, impediments to rapid recovery, and any decisions made about the building. These inputs were loaded into SP3 to predict each building's seismic performance under the earthquake scenario. Output analyses were produced by using several analytical tools, models, functions, and assumptions within SP3.

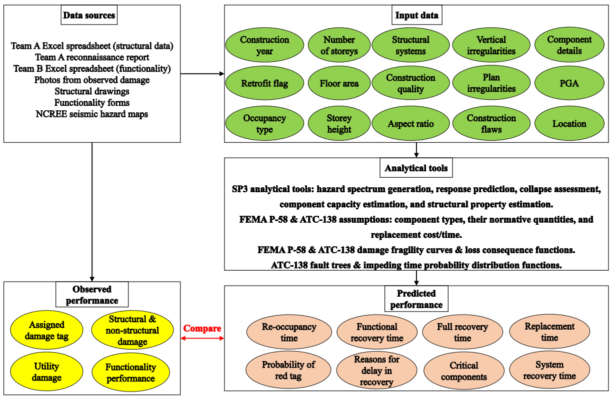

Figure 5: The benchmarking procedure used in this study.

The methodology uses a hazard spectrum generator that estimates the earthquake spectrum at each building's location relative to the epicentre. This spectrum is then scaled according to the recorded PGA. The response prediction engine estimates storey drift ratios, floor accelerations, and residual drifts based on the chosen intensity measure, using structural properties that are, in turn, estimated from the provided structural inputs. SP3 also estimates building collapse capacity and component seismic capacities, given the required inputs for each component. Furthermore, FEMA P-58 damage fragility curves determine the expected level of damage for each building component given the structural response [3]. Following that, FEMA P-58 loss consequence functions quantify expected loss measures, such as repair costs and repair times for each component, given the level of damage incurred [17]. In this exercise, the scenario expected loss (SEL) was used, which represents the expected post-earthquake repair cost of the building as a percentage of its replacement cost. The replacement cost is the cost expected if the building were demolished and replaced in-kind.

To account for lower repair costs in Taiwan than in the USA, this study applied a regional cost scale factor of 0.6. It assumes that repairing a building component would cost 40% less in Taiwan than it would in the USA. This regional cost scale factor also applies to the building replacement cost. Finally, ATC-138 fault trees were used to determine functionality at the component, system, and building levels, based on the damage state of each component [9,25]. Moreover, SP3 estimates the expected time required to conduct activities such as damage inspection, financing, and resource mobilisation based on the corresponding probability distribution functions defined in the ATC-138 framework. There are also several assumptions about the expected types of structural and non-structural components and their normative quantities within the building, as well as about the cost and time required to replace the building. Available data of this kind, collected during reconnaissance, were used. Where such data were unavailable, the default assumptions in SP3 were used in the analysis.

The outputs of FEMA P-58 analyses are in the form of expected repair costs and recovery times for a building to reach re-occupancy, functional recovery, and full recovery performance states [27]. Furthermore, the expected recovery time for each system, such as structural, conveying, and electrical systems, can be extracted separately. FEMA P-58 guidelines can also estimate the expected probability of unsafe placarding of buildings using red placards, based on structural damage state and critical building components (structural and non-structural) that would delay recovery.

Table 1: Collected data from the 16 buildings visited.

Building ID	Building type	Structural system	Year built	Placard*	Retrofitted	Structural damage	Non-structural damage	Utility damage	Recovery time	Reasons for loss/lack of functionality
S03	Residential (six floors)	RC frame (infill) + RC wall	1993	Green	Yes (2019)	• Shear cracks in retrofitted walls • Flexural cracks on columns	• None	None	Fully functional	No loss of functionality; however, residents moved to an emergency shelter for 5 days due to fear of aftershocks.
O89	Residential (six floors)	RC frame	1994	Green	Yes (2019)	• Shear cracks in retrofitted walls	• One elevator • Non-structural partitions damaged at ground floor (toppling and cracking)	Localised water pipes	Fully functional	A water tank was used to manually pump water to households while the water pipes were under repair for 15 days.
A11	Hotel (six floors, two buildings)	RC frame (no infill) + RC wall + BRB	1967	Green	Yes (2013)	• Minor damage in the seismic gap between two buildings • Minor cracking in cladding at bases of exterior columns	• None	No water and power until April 20 due to the demolition of the Uranus Building	2 months	Minor repairs were postponed for 1 month until April 28, when the demolition of Uranus Building was completed, and the road cordon was lifted; May 29 re-opened; interior works ongoing; labour shortages due to the isolated location of Hualien.
E11	Residential high-rise (10 floors)	RC frame (infill)	1991–1998	Red & yellow	No	• Heavy damage (axial failure) to interior columns of short frames and thin walls	• Egress, elevators, considerable damage to non-structural facade and internal partitions (masonry and concrete infills)	Water pipes broken	Not functional	Repair would require the complete reinstatement of several columns and walls. Approximately 400 people living in this complex were reported to be living with families and friends or in emergency accommodation.
B02	Residential and commercial (four storeys)	RC frame (infill) + RC wall	1977	Red	No	• Loss of core concrete and initiation of buckling in all circular columns over the footpath • Insufficient hoops and failure of lap in most columns	• Stairways and ceilings	Water pipes broken	Not functional	A column supporting the arcade was severely damaged, and all the concrete fell off. The plan was to repair and strengthen. The hotel opposite collapsed during the April 23 aftershock and was demolished. The road was cordoned off for 15 days. Shops on the road started re-opening around May 10.
B05	Hotel (12 storeys)	RC frame (infill) + RC wall	1997	Red	No	• Failure of first-storey columns	• Significant shear cracking in non-structural walls above level 1	N/A	Demolished	The building survived initial shaking but sustained significant damage to columns. Before completing repairs, the April 23 aftershock caused irreparable damage to first-storey columns. The building had been partially demolished by the time of the reconnaissance. Hotel owner plans to self-fund the rebuild.
E18	Residential (six floors)	RC frame (no infill) + RC wall	1993	Green	Yes (2021)	• None – Little evidence of damage	• None	None	Fully functional	Infill wall and wingwall retrofit up to the height of the building; light cracking on walls, but very little evidence of damage; old fire protection devices: fire extinguisher; no fire sprinklers installed.

Building ID	Building type	Structural system	Year built	Placard*	Retrofitted	Structural damage	Non-structural damage	Utility damage	Recovery time	Reasons for loss/lack of functionality
B03	Residential and commercial (12 floors, second floor commercial)	RC frame (infill) + RC wall	1992	Red	No	• Crushing of wing walls at the third storey • Out-of-plane failure of masonry walls	• Shear failure of non-structural RC walls • Cladding and internal partitions, elevators, and stairwell partitions	None	Not functional	Red (April 3 yellow and then April 9 red); while not a dangerous building, the decision was to repair structurally from B1 to level 9, mainly floors 2, 3, 4 and 5; damage to non-structural components was severe and significant; second-floor shops and apartment units above were empty as occupants moved out.
D13	Residential high-rise (17 floors)	RC frame (infill) + RC wall	1996	Yellow	No	• Shear failure of exterior concrete partition walls up to the height of the building • Shear failures on walls and columns between ground floor and level one	• Stairwell damage to URM partitions • Elevators • Damage to external concrete infill partitions, including linings (tiles)	Water pipes broken and water leakage	Partially functional	Shear failures of walls were visible, three out of four elevators were damaged, one functional; majority of residents (128 households) had moved out; falling hazards from the tiles on exterior walls were significant, not only for households but also for foot traffic.
E08	Shops (ground floor), residential upper floors (four floors)	RC frame (masonry infill)	1979	Red	No	• Transverse wall had significant damage • Rocking and diagonal shear cracking in URM piers • Significant cracking in floor diaphragm	• Damage to URM partitions around openings on ground floor • Cracking in cladding tiles due to damage to external partitions • Failure of stairs	None	Not functional	An illegal additional bay and additional storey; plan irregularity due to the offset of the centre of mass and centre of stiffness. Moderate cracking in longitudinal walls vs significant cracking in the sole transverse wall. Cracking in cladding tiles; tiles popped; however, insignificant cracking in concrete elements. Diagonal shear cracking in longitudinal infill walls. Signs of infill walls causing shear cracking in columns at the ends of the strut. Failure of stairs.
A03	Commercial building (four storeys)	RC frame (infill) + RC wall	1969	Yellow in mainshock, then red in aftershocks	No	• Concrete crushing at base of RC shear wall • Axial failure of exterior corner column • Crushing of concrete near joints in exterior columns	• Damage to ground-floor masonry partitions and stairwell	Loss of water during aftershocks	Not functional	Lost use of water utilities during the aftershock; the original owner applied for a seismic assessment under the new government policy. The seismic capacity of the structure was determined to be insufficient, and the owner decided not to upgrade and sold the building to a new owner 3 months before the 2024 earthquake.
D10	Office building (six floors)	RC frame (infill) + RC wall	1968	Yellow	Yes	• Shear failure of column • Shear failure in short-span shear walls in x-direction • Shear failure in shear walls in y-direction • Shear failure of columns bounding wing walls	• Elevators • Damage to URM partitions, doors, and concrete infill walls	Pipe burst and water leakage during aftershocks	Partially functional	The office building has been operational since the April 3 earthquake. Utilities and elevators are also functional. The owner wanted to strengthen the building by adding shear walls and expanding the ground-floor columns. The building was operational even during strengthening.

Building ID	Building type	Structural system	Year built	Placard*	Retrofitted	Structural damage	Non-structural damage	Utility damage	Recovery time	Reasons for loss/lack of functionality
C04	Commercial and residential building (three floors)	RC frame (no infill) + RC wall	1996	Yellow	No	• Permanent building rotation, 50mm of permanent roof drift	• Door jamb • Water tank on the roof was broken and fell	None	6–9 months	Safe for occupancy; Settlement of soil under an 8-storey building foundation caused nearby buildings to tilt; Repair can be challenging as there is no access to the tilted side of the building; the owner chose to cover the yellow placard, as many customers had queried. The realignment of the house will not take place after the Mid-Autumn Festival on October 6, 2024, due to a shortage of engineers, with an estimated 3 months' work.
D07	Hotel (five floors)	RC frame (no infill) with RC wall	2015	Green	Yes (2017)	• None	• None	None	Fully functional	The owner is a contractor; a good example of a new build. Only minor cracks on the front door footpath.
O67	Commercial and residential (15 storeys)	RC frame (infill) + RC wall	1994	Red	No	• Shear failure of RC walls and RC beams • Flexural cracks on columns • Shear failure of exterior RC partition walls	• Buckling of metal shutter • Interior ceiling panel failure • Exterior concrete infills damaged with consequent exterior tiles cracking and falling • Window damage	None	Not functional	Overall damage severe – shear damage to walls, damage to non-structural components with interior ceilings and tiles also fell off; residents (118 households) have all moved out, and had recently voted for strengthening.
D12	Residential (16 floors, two buildings joined with a corridor, each with 121 households)	RC frame (infill) + RC walls	1994	Yellow	No	• Damage to shear walls along x-direction • Damage to the coupling beams of the core walls in x-direction from levels 1–7	• Elevators • Damage to suspended ceiling at lobby • Damage to internal URM partitions and external concrete infills with tile dislodgement • Damage to internal linings and large tile dislodgement	None	Partially functional	The old elevator when the building was built was damaged and it took 25 days to be repaired; Building A appeared to have suffered more damage, with water leakages in the basement which is car park; most households who were renters lived below the sixth floor have moved out as there is $8,000 (TWD) rent subsidies and it is safer and more economical to receive this subsidy and rent somewhere else.

**The official rapid building assessment (RBA) only assigned red or yellow placards to damaged buildings; there were no green placards. No placard/tag signified a 'green' rating (i.e., buildings could be used). The green placards in this Table refer to the placards assigned by the NCREE/NZRS/Japanese reconnaissance team (Team A), which were equivalent to no placard assigned by RBA officials. Abbreviations: BRB = Buckling-restrained braces; RC = Reinforced concrete; URM = Unreinforced masonry.*

RESULTS

Damage and Functional Recovery of Buildings

The team observed rapid post-disaster recovery, with Hualien City remaining fully functional 1 month after the earthquake. It was noted that buildings demonstrated high resilience and that the swift restoration of earthquake-damaged infrastructure contributed to minimal utility disruptions. In one case involving four apartment buildings with damaged water pipes, the building management team utilised backup water tanks and pumps to manually supply water to each household.

As reported by Lee et al. (2025) [30], the buildings that received red placards had significant damage to their structural systems. The primary causes of damage among the 16 buildings included soft-storey mechanisms caused by vertical irregularities, particularly in mixed-use buildings with open-plan commercial ground floors and residential upper levels with a higher proportion of partition walls. Additional contributing factors were poor seismic detailing in structures constructed before the 1999 Chi-Chi Earthquake, such as lap splices in plastic hinge regions, insufficient transverse reinforcement, lack of joint confinement, low concrete strength, and plan irregularities that resulted in torsional response. In several cases, buildings were assigned a red placard due to failures of external facade elements that posed significant safety hazards, even when the main structural system remained largely intact.

Failure of non-structural components was the primary reason some structurally intact buildings were assigned a yellow placard, rendering them uninhabitable.

The most common damage observed for non-structural components included:

- Damage to egresses and elevators
- Damage to facades and glazing
- Damage to ceilings
- Damage to partitions

In the buildings with red and yellow placards, debris from failed infill walls was found hampering safe egress. Defunct elevators were also commonly observed in most of these buildings. wall infill cracking also observed in some of them. Such cracking mechanism caused exterior tiles to crumble and fall and compromised the building's weathertightness. Broken glass from buildings with damaged window glazing was observed. Falling tiles and broken glass became significant hazards to pedestrians and the residents still occupying these buildings. Damage to the ceilings in some buildings exposed the services associated with the heating, ventilation, air-conditioning, and cooling (HVAC) system, as well as leaving general electrical conduits hanging. This also posed a life-safety risk and largely affected residents and the public regarding the building's perceived safety.

The observed damage to partitions exhibited consistent patterns attributable to the construction techniques employed. Given the frequent typhoons in Taiwan, concrete infill panels were incorporated around the exterior perimeter of buildings to provide additional out-of-plane strength and resistance against wind pressure and projectiles. These infill panels typically include single layer of reinforcement at mid-thickness, with nominal amount. Additionally, they are tiled to enhance waterproofing and embellish the building's exterior.

Local architects and engineers shared with the reconnaissance team that these infill panels are classified as "architectural" or "non-structural" and are not part of the primary lateral resisting system. Consequently, they have traditionally been excluded from the structural design of vertical lateral systems. When drifts are concentrated, these panels create additional stiff, yet weak, load paths for seismic demands, leading to complex unintended interactions with columns, beams, and the main structural systems. In several instances, their damage prevented harm to the primary lateral system, as these exterior infill frames inadvertently acted as the main lateral system.

Internal partitions were predominantly constructed with unreinforced masonry. Damage was frequently observed in the lower storeys, around stairwells and at openings, such as windows and doors. In many instances, this damage led to the collapse or toppling of heavy linings, obstructing egress. Damage to both external and internal partitions often led to short-term functionality loss. In most cases, repairing this type of damage was among the most significant cost items due to its considerable and widespread nature around the building's perimeter.

Case Studies of Selected Buildings

As shown in Table 1, the 16 buildings visited encompassed a range of building types and damage states, as indicated by the placards received. This section presents detailed results for six case study buildings, which are representative of the 16 buildings observed, in terms of building type, structural systems used, and placards received. Table 2 summarises the benchmarking results of the FEMA P-58 framework compared to observed data. The impeding factors that contextually affected the functional state of individual buildings are also discussed.

(1) Residential apartment – No placard (i.e., green placard for the purpose of this paper).

Building S03 is a six-storey residential building, constructed in 1993. The lateral load-bearing system of the building consists of RC moment-resisting frame (MRF) with unreinforced masonry (URM) infills. The residential complex has 36 units, and the building's first floor is used for car parking. The building has a total height of 25m, with a first-floor height of 3.9m and subsequent floors at 3m. The floor area of each storey is 935m^2. The building has 36 columns measuring 35cm by 60cm. The building was retrofitted in 2019 after it was damaged in the Mw 6.4 earthquake on February 6, 2018. The retrofit programme consisted of adding four 30 cm-thick RC walls and jacketing columns at the ground floor. Figures 6a–c respectively show the street view, elevation view, and plan view of the building.

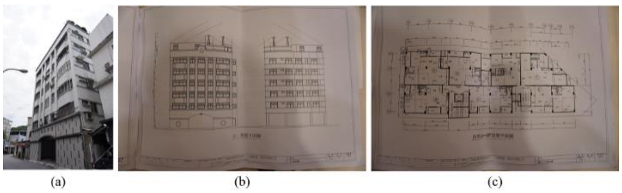

Figure 6: (a) street view, (b) elevation view, and (c) plan view of Building S03.

The PGA experienced at the building's location was recorded as 0.4g. The reconnaissance records indicate that Building S03 performed satisfactorily and received no placard. As shown in Figure 7, there were minor flexural cracks with a 0.2mm to 0.3mm width on some columns, as well as a few shear cracks on RC walls. The cracks were only on the parts that had already been damaged in the Mw 6.4 earthquake on February 6, 2018 and had been repaired and strengthened in the retrofit programme. Residents moved out of this building immediately after the earthquake and stayed in the emergency shelter out of fear of aftershocks. The building was re-occupied 5 days after the earthquake.

Table 2: Summary of FEMA P-58 benchmark results of case study buildings.

Building	Benchmarking result	Reasons for discrepancy
S03	• Damage state prediction aligned with observed data • Predicted re-occupancy time was longer	• FEMA-P58 predicted damage to elevators and HVAC systems, which would require a longer time to repair and for households to re-occupy the buildings • Fire safety requirements, individual household preparedness and adaptive resilience
A11	• Prediction for minor structural damage aligned with observed data • Predicted repair/recovery time did not consider external impediments such as road cordons	• The impact of adjacent or nearby buildings, and the need for demolition and road cordon on the repair time, was not in the scope of FEMA P-58 analysis
D13	• Predictions of damage to both structural and non-structural components aligned with observed data	• N/A
D10	• Predicted damage states aligned with observed data • Predicted recovery timeframes were longer than what was observed	• The longer recovery times predicted in the FEMA P-58 analysis were related to the requirement for functional non-structural components for the building's functional recovery • Building occupants' self-adaptive capacity to accommodate inconveniences, such as accessing the office without using elevators, means the building could be used while being repaired
C04	• The prediction of the damage state was different from the observed damage • The tilting of the building due to the ground settlement was caused by the adjacent building	• External site effects due to nearby buildings were outside the scope of the FEMA P-58 analysis
O67	• Prediction for damage to both structural and non-structural components aligned with observed data	• N/A

Figure 7: Observed damage to Building S03.

The outputs of the seismic risk and recovery assessment of the building using the FEMA P-58 [3] and ATC-138 [9,25] frameworks, the SP3 software [32], and the 2024 Mw 7.4 Hualien Earthquake scenario showed a predicted mean SEL of 6%. The prediction for re-occupancy of Building S03 was 29 days.

Furthermore, the probability of the building receiving a red placard was low at 3.4%, and structural components were expected to function immediately. These results indicate that the building was expected to exhibit good structural performance, which aligns with the observed result. However, the predicted re-occupancy time (29 days) is longer than the observed time. This is mostly due to the predicted failure of some non-structural components required for function (due to their high vulnerability). For instance, it was predicted that damage to the elevator, HVAC, and ventilation systems would prolong functional recovery. It also predicted that damage to the fire suppression system (sprinklers) would delay re-occupancy. However, local conditions suggest that manual suppression systems, such as fire extinguishers, are sufficient to meet fire safety requirements, so a functional sprinkler system is not necessary for re-occupancy. Figure 8a shows an example of the manual fire safety system in this building with extinguishers in place.

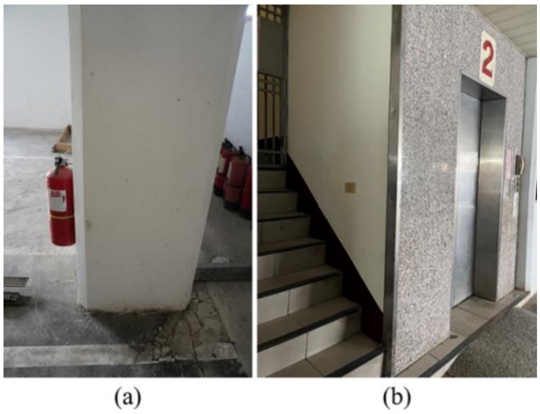

Figure 8: (a) manual fire extinguishers and (b) functional elevator post-earthquake in Building S03.

Such predictions were produced based on the default assumption of non-structural elements in SP3. Those defaults assumed that the building had non-anchored non-structural components that were not seismically pre-qualified. In addition to the fire system reported above, the elevator in this building sustained little damage and remained functional after the earthquake (see Figure 8b).

The SP3 analysis was later adjusted to account for local fire safety standards and select higher-quality, better-designed, and seismically pre-qualified HVAC and elevator components with proper anchorage, the expected time to re-occupancy and functional recovery decreased to 2 and 15 days, respectively. These revised recovery times better align with data collected during reconnaissance observations. It is worth noting that residents' tolerance and adaptability to changes in the comfort level a building could offer were high. In a few cases where the household mechanical cooling system, such as an air-conditioning unit, was damaged, residents who had re-occupied the building used portable fans, showing this high tolerance and adaptability behaviour.

(2) Commercial building hotel – No placard (i.e., green placard for the purpose of this paper)

Building A11 was a six-storey hotel (Hotel Les Champs Hualien) built in 1967. It has two buildings, A11-1 and A11-2, that were constructed adjacent to each other. Figure 9a shows the street view and the position of Buildings A11-1 and A11-2. The lateral load-bearing systems of these RC buildings were RC walls. The building had been retrofitted after the Mw 6.4

earthquake on February 6, 2018. The retrofit programme was self-funded and consisted of installing BRBs, as shown in Figure 9b. The building had a total height of 18m, with the first floor at 3.8m and the other floors at 3.2m. Figure shows the elevation view of this building from all directions. The plan dimensions of the building were 23.9m by 13.6m, and the typical floor area per storey was 325m^2. Figure 11 shows the plan view of this building.

Figure 9: (a) street view of Building A11 and (b) BRB frame within the building.

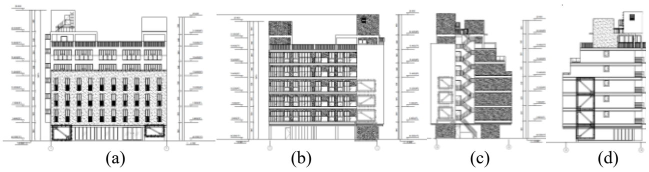

Figure 10: Elevation view of Building A11 from (a) front, (b) back, (c and d) sides.

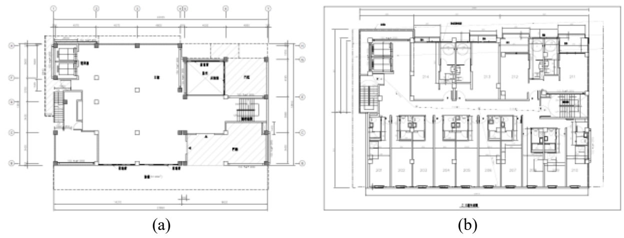

Figure 11: Plan view of Building A11: (a) first floor and (b) typical floor.

The PGA experienced at the building's location was recorded as 0.44g. The building showed relatively good performance following the earthquake and had no placard (i.e., green placard for the purpose of this paper). However, minor structural damage was observed. As shown in Figure 12, some welds connecting the BRB to the steel gusset frames fractured during the earthquake. There was also minor damage at the seismic gap between Buildings A11-1 and A11-2. Minor cracking was observed in the cladding surrounding the concrete columns at the base of the exterior columns.

Figure 12: Observed damage to Building A11.

Reconnaissance found that the building had no water and power for 17 days due to the demolition of the Uranus Building, which collapsed in the earthquake and was located opposite Building A11. The repairs to Building A11 were postponed for 25 days due to the closure of road access during the demolition of the Uranus Building. After the cordons were lifted, the repair work took 1 month, after which the hotel could re-open. At the time of the reconnaissance, some interior work was still ongoing. The hotel owner reported that one of the major impediments to building repairs was a labour shortage. Labour shortage appears to be a common problem in Hualien due to its geographic isolation, which makes transporting labour and materials more costly than in the rest of Taiwan.

The outputs from the seismic risk and recovery assessment of the building indicate a predicted mean SEL of 16%. Moreover, the expected recovery time of the building was calculated as follows: 8 days to achieve re-occupancy, 93 days to functional recovery, and 111 days to full recovery. The expected probability of the building being allocated a red placard following the scenario earthquake was 40%, and there was a 31% probability that structural damage would delay re-occupancy and functional recovery by more than 1 month. These predictions appear to align with the building's observed structural seismic performance.

After changing the construction quality to satisfactory for non-structural components in SP3 analysis, the expected time to functional recovery changed to 53 days. This predicted functional recovery time did not decrease as significantly as in the earlier case study of Building S03, where enhanced construction quality was assumed for elevators and HVAC systems. The main reason for this is that the significant structural damage largely determined the recovery of this building. Another interesting finding from such benchmarking is the impact of adjacent or nearby buildings and the need for demolition and road cordons on repair time; however, these factors were not considered in the FEMA P-58 analysis. This is because SP3 only models seismic damage and losses to the building premises, and disruptions caused by neighbouring buildings are beyond its scope of analysis.

(3) High-rise residential building – Yellow placard

Building D13 was a U-shaped, seventeen-storey high-rise building constructed in 1996, with a large courtyard. The building had a mixed occupancy: the ground floor had commercial use, and the upper floors had residential use. The lateral systems of the building consisted of RC MRFs and RC shear walls. The building's total height was 50m, with the first floor at 3.2m and the other storeys at 2.9m. The floor area was 904m^2. Figure 13a–c present the street, elevation, and plan view of the building. The building had a large shear wall in the courtyard with visible reinforcement in a diagonal configuration. The concrete walls appeared thin and singly reinforced. Some walls had a large number of pipes running through them. There were several large-sized columns as well. There appeared to be soil subsidence due to liquefaction around the building, due to the proximity to the Meilun River. Relative settlement suggested the building was founded on piles.

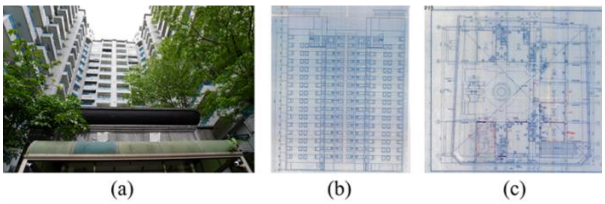

Figure 13: (a) street view, (b) elevation view, and (c) plan view of Building D13.

The experienced PGA at the building's location was recorded as 0.4g. The reconnaissance data suggest that the building showed poor structural and non-structural seismic performance. A yellow placard was officially placed. The majority of the 128 household residents had moved out by the time of the visit.

Damage to the building was extensive but seemed repairable. Distributed shear failures were observed in walls and columns between the ground floor and the floor above. Shear failure was observed in the exterior concrete partition walls at all levels of the building. Sliding failures were also observed in the shear walls of some stairwells, making egress difficult. Moreover, large cracks were seen in the diaphragm at locations where walls terminated on the second floor due to the transfer of forces to the columns.

Non-structural damage was also observed. There was damage to URM partitions around the openings on the ground floor. Falling hazards from exterior tiles were a major concern for households and foot traffic. Shear failure was also observed on the masonry infill walls at the ground floor. Three of four elevators were damaged and inoperable. Water pipes were broken, and there were water leaks. Figure 14 shows instances of the observed damage to the building. Several other tall residential buildings nearby sustained only minor damage compared to Building D13; however, the explanation for this has not been established.

Figure 14: Observed damage to Building D13.

SP3 analysis predicted a mean SEL of 23%. The building recovery time was estimated to be 150 days to achieve re-occupancy, 204 days to functional recovery, and 642 days to full recovery. If demolished and rebuilt, the expected replacement time was 1,320 days. The expected probability of the building receiving a red placard was 52%, and damage to structural components and stairs was the primary cause of delayed re-occupancy. These seem to align with the poor structural seismic performance observed in Building D13. A probability of 50% or higher of being assigned a red placard suggests that the building is expected to require major repairs.

However, a moderate level of predicted mean SEL suggests that the building is still repairable. SP3 also accurately predicted the observed non-structural damages to the building. For example, there was a 55% probability that exterior cladding would have damage states that would pose an exterior falling hazard. A 30% probability of functional recovery within 6 months was suggested for interior elements. Furthermore, there was a 62% probability that damages to the three elevators would delay functional recovery by more than 1 month. There was also a 32% and 36% probability that damage to potable water and sanitary plumbing, respectively, would each add 1 month to the building recovery time.

(4) Office building – Yellow placard

Building D10 was a six-storey office building for a news agency constructed in 1968. The lateral load-bearing system consisted of RC MRF and RC shear walls. The ground floor of the building had been retrofitted before the earthquake. The height of the building was 18m, where the height of the two bottom floors was 3.3m and 3.2m respectively, and a floor height of 3m for the other storeys. The floor area was 650m^2. RC shear walls had short spans along the x-axis. Figure 15a–c presents the street view, elevation view, and plan view of Building D10.

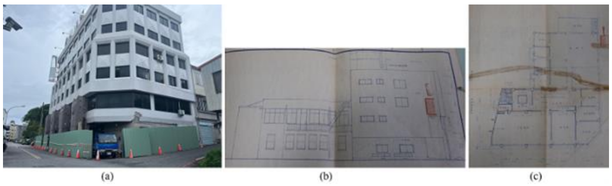

Figure 15: (a) street view, (b) elevation view, and (c) plan view of Building D10.

The PGA experienced at the building's location was recorded as 0.44g. The building was occupied after the earthquake, and at the time of reconnaissance, despite slight to moderate structural damage being observed. The building was officially assigned a yellow placard. As shown in Figure 16, shear failure of one column was observed. There were visible cracks in the masonry infill walls, especially around the south corner of the building. There were also visible cracks at the base of columns around openings of the RC shear walls along the y-axis.

Utilities functioned continuously after the earthquake. However, several non-structural elements suffered some damage: URM partitions, doors, and concrete infill walls. Water pipes were damaged in the aftershocks, leading to water leaks. One elevator was damaged. However, the damage observed did not affect the continued use of the building. After the earthquake, the building owner decided to strengthen the building by adding shear walls and expanding the ground-floor columns. The building remained operational while undergoing staged strengthening.

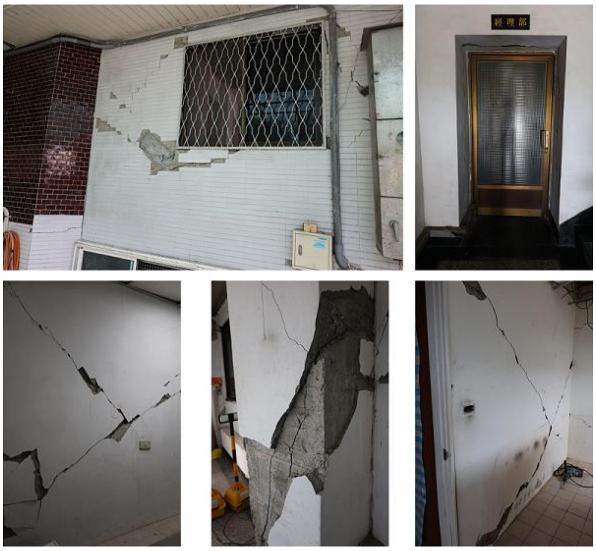

Figure 16: Observed damage to Building D10.

In the SP3 analysis, a predicted mean SEL of 11% was reported. The recovery time for the building was estimated at 5 days to achieve re-occupancy, 105 days to functional recovery, and 246 days to full recovery. The expected probability of the building having a red placard was 35%. The probability of a delay of more than 1 month in repairing structural damage was predicted to be 33%. A low mean SEL (11%) and a moderate likelihood of having a red placard (35%) suggest the building would have sustained limited damage. This aligned with the building's overall seismic performance. SP3 also predicted a 68% probability that damage to elevators would delay functional recovery by more than 1 month, as well as a 30% probability that damage to potable water plumbing and sanitary plumbing would delay functional recovery by more than 1 month.

Overall, the predicted recovery timeframes were longer than what was observed. Although both structural and non-structural components were damaged, the building remained functional.

When we removed the requirement for functional non-structural components for the building's functional recovery from the SP3 model, the expected time to functional recovery decreased to 34 days. Accordingly, the re-occupancy time and the readjusted functional recovery time correspond to 0.5% and 3.5% of the building replacement time. Such an adjustment within the SP3 model produces better alignment with the observed data.

(5) Mixed low-rise building type – Commercial and residential, yellow placard

Building C04 was a three-storey building constructed in 1996. The lateral load-bearing system of the building consisted of RC MRF (no infill) with RC walls. The ground floor was a drink store, and the upper floors were used for residential purposes. The building had a total height of 12m. The typical floor area was 43.8m^2. Figure 17a–c shows the street view, elevation view, and plan view of the building.

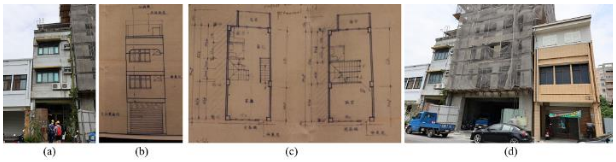

Figure 17: (a) street view, (b) elevation view, and (c) plan view of Building C04; (d) the adjacent eight-storey building.

The PGA experienced at the building's location was recorded as 0.44g. The reconnaissance records indicate that building C04 sustained moderate damage. The building was assigned a yellow placard. Figure 18a–c presents various types of damage observed. The building was safe for occupancy following the earthquake, but it tilted towards the adjacent eight-storey building due to foundation damage caused by ground settlement beneath the eight-storey building, as shown in Figure 17d. There was also minor pounding damage to a similar height building on the opposite side, as shown in Figure 17a. Permanent building rotation was observed with a 50mm permanent roof drift. As shown in Figure 18b, the front door was jammed, which suggests storey drifts in addition to overall rotation of the building. Furthermore, damage to the rooftop water tank was reported.

Repair of the building will require re-levelling. However, access to the tilted side of the building would be extremely difficult, as shown in Figure 18a. The building owner had covered the yellow placard on the front door to address concerns expressed by shop customers about the building's safety. It was reported that the building would be righted after the Mid-Autumn Festival on October 6, 2024, 6 months after the earthquake, due to the time required to mobilise engineers and contractors.

Figure 18: (a) pounding damage to the adjacent building, (b) door jamming, and (c) pavement cracks and content damage.

SP3 analysis showed a predicted mean SEL of 13%. The recovery time of the building was predicted to be 4 days to achieve re-occupancy, 54 days to functional recovery, and 57 days to full recovery. If the building were demolished and rebuilt, the expected time to replacement would be 504 days. The expected probability of the building having a red placard assigned was 9%. These results, however, suggest a relatively good performance of the building, which is contrary to the observed damage. This is not surprising given that the tilting of the building, which is the main source of damage, is not possible for SP3 to consider, as an adjacent building beyond the premises of Building C04 caused the ground settlement. Without accounting for the building's tilt, SP3 predicted that the building would have had satisfactory seismic performance.

(6) Mixed high-rise building type – Residential and commercial, red placard

Building O67 was a 15-storey building constructed in 1994. The building consisted of two identical buildings separated by a seismic gap. The building's occupancy was mixed, with the ground floor used for commercial shops and the upper floors for residential use. The lateral load-bearing system of the building consisted of RC MRF with URM infills and RC walls. The building had a total height of 46m, with the first floor 3.6m high and the other storeys 3m high. The floor area was 432 m^2. Figure 19a–c illustrates the street, elevation, and plan view of the building.

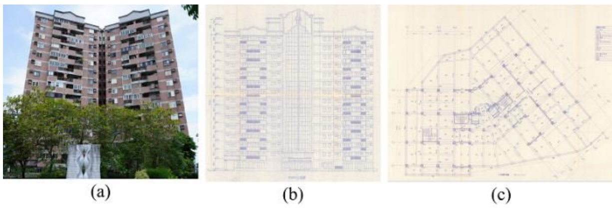

Figure 19: (a) street view, (b) elevation view, and (c) plan view of Building O67.

The PGA experienced at the building's location was recorded as 0.41g. Building O67 showed a poor seismic performance following the earthquake. It was assigned a red placard. All 118 households had vacated the building. As shown in Figure 20, structural damage included shear failure of an RC wall in the staircase, shear failure of beams, shear failure of RC exterior partition infill walls above the second floor, and shear failure of hanging walls with a horizontal reinforcement fracture. Damage to several non-structural elements included damage to interior suspended ceiling panels. There were large diagonal cracks in the exterior tiles due to damage to the exterior concrete infills, creating a considerable falling hazard The building manager had shut down power and water, but there was no reported disruption to the utility supply.

Figure 20: Observed damage to Building O67.

The SP3 analysis predicted a mean SEL of 23%. The recovery time for the building was estimated at 147 days to achieve re-occupancy, 150 days to functional recovery, and 156 days to full recovery. If a demolition and rebuild decision were made, the building's replacement time was expected to be 1,104 days. The probability of the building having a red placard was predicted to be 88%, with the structural damage being the primary cause of delay in re-occupancy.

The high probability of a red placard, as predicted by SP3, aligns with the poor structural seismic performance observed during the reconnaissance. However, a moderate expected mean SEL suggests that the building could be repairable despite the significant damage. The debris from the interior elements and damage to the stairwell impeded safe egress and were the primary causes of delay for building re-occupancy. There was a 34% probability that the damage to the interior space would delay functional recovery by more than 6 months. By the time of reconnaissance, the team was informed that most residents had voted to repair and strengthen the building, rather than demolish and rebuild.

DISCUSSION

This section discusses the study's results and draws insights from the reconnaissance on functional recovery and the FEMA P-58 benchmarking process. Figure 21a–c compares the SP3-predicted performance of all 16 Hualien buildings shown in Table 1 and with their corresponding observed performance recorded during the reconnaissance. For this set of buildings, predicted performance has been presented as expected SEL and normalised recovery time. In Figure 21, $T_{recovery}$ and $T_{replacement}$ represent recovery time and replacement time of the building, respectively. The recovery time is shown for both re-occupancy and functional recovery performance states. In Figure 21, the recovery timeframes are normalised to the replacement time of the corresponding building. The normalisation is to account for the effect of building size, as larger buildings may have a longer expected recovery time. The pattern in Figure 21 suggests a higher predicted SEL and recovery time for buildings with a red placard when compared with buildings with a green placard.

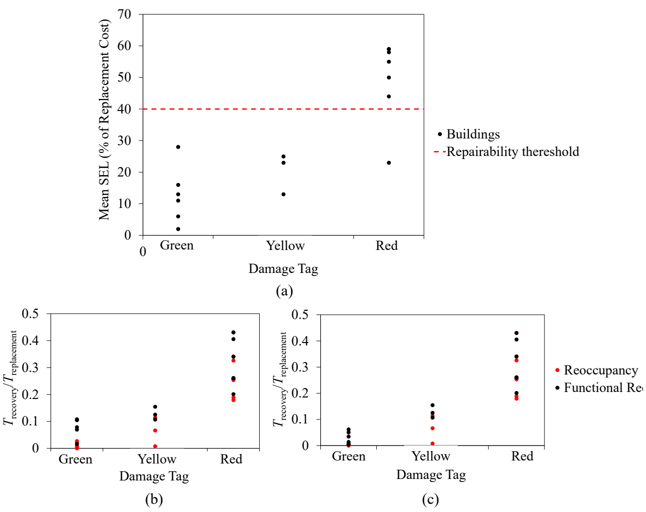

Figure 21: Benchmarking outputs for all the buildings in terms of: (a) mean SEL; normalised recovery time with (b) default SP3 assumptions and (c) better-quality non-structural components for slightly damaged buildings.

Figure 21a shows that almost all the buildings with red placards had a predicted SEL of over 40%. According to the FEMA P-58 framework [3], the building repairability threshold is set at a repair-to-replacement cost ratio of 40%. In other words, it is estimated that repairing a damaged building would be economically justifiable only if the cost is less than 40% of its replacement cost. SP3 appears to have accurately predicted which buildings need to be demolished and replaced following the earthquake, with a predicted SEL of above 40%. Data on repair costs for many buildings were unavailable at the time of reconnaissance. A longitudinal recovery reconnaissance is needed to collect repair cost data so that the prediction of repair costs using FEMA P-58 can be further benchmarked, as in previous studies such as the 1994 Northridge Earthquake [25], the 2009 L'Aquila Earthquake [24], and the 2010/2011 Canterbury Earthquake sequence [23].

As shown in Figure 21b, the recovery time required for buildings with red placards appears consistent between the observed data and SP3 predictions. Moreover, Figure 21c shows that for buildings that received no placard, SP3's predictions of damage and functionality match the observed building performance, with non-structural components such as HVAC units and elevators remaining functional. The discrepancy between the observed and the predicted performance is resolved in Figure 21c, where local conditions and higher quality and anchorage of non-structural elements are considered. In contrast, the buildings with a red placard are predicted to have a poor structural performance, and their long recovery time is mainly due to their extensive structural damage, even if better-quality non-structural components were used.

Overall, this study showed that the FEMA P-58 methodology, as implemented by SP3, can accurately predict the structural performance of buildings following a damaging earthquake. This benchmark result is consistent with similar benchmarking of FEMA P-59 performance predictions against observed earthquake data from the 2010/11 Canterbury Earthquake sequence [22-23]. Also, the seismic performance of drift-sensitive non-structural components, such as partition walls, stairs, and cladding, was predicted with acceptable precision. However, performance predictions for acceleration-sensitive non-structural components, such as elevators, HVAC systems, and plumbing, appear overly conservative. As mentioned before, it is understood that this is largely due to an underestimation of these components' capacity to respond to the applied seismic demand. This conclusion remains true for those buildings that had better-quality non-structural construction installed. Good quality of non-structural elements refers to those properly anchored, seismically pre-qualified, and designed to higher criteria than the minimum requirements of design standards [5,34].

FEMA P-58 benchmarking of these 16 buildings also identified contextual factors and community resilience beyond the scope of its analysis. People's risk perception regarding building damage, tolerance of inferior living conditions, and adaptive ability, which affect the functional state of a building, are out of scope for FEMA P-58, as shown in the SP3 results. Observed examples included people's tolerance and acceptance of using stairs in high-rise buildings where elevators were extensively damaged, and the use of portable fans when the mechanical air-conditioning system was damaged. A similar human risk perception element was also found to be a key factor affecting hospital staff's decision to evacuate or stay in hospital buildings following the Türkiye Earthquake sequence in 2023 [26,35].

Across 16 buildings visited, there was no report of building functionality loss due to damage to HVAC or elevators in the buildings with green and yellow placards. As shown in two residential buildings, E18 and S03, where a fire sprinkler system was absent, fire protection devices, namely fire extinguishers, were used and accepted. Fire safety standards vary across regions, and these differences may differ from the SP3 default assumptions; thus, further calibration of these assumptions is needed.

Our benchmarking analysis also suggested that FEMA P-58 predictions using SP3 performed well in assessing the seismic risk of individual buildings. When the comparison metrics for predicted and observed building performance were not aligned, influences from neighbouring or adjacent buildings were observed. For instance, disruptive effects from nearby buildings due to extensive damage or collapse, and the need to safely demolish them, led to the placement of a safety cordon, which further impeded the functional recovery of several buildings and disrupted businesses. Similarly, in another example observed during reconnaissance, the geotechnical aspects of the building site, such as pounding damage from an adjacent building, led to ground settlement, the tilt of the building, and a long recovery time was expected.

These benchmark exercise and analysis results highlight the importance of further research to quantify the effects of those 'out of scope' impeding factors, namely, building site effects, the quality of non-structural components, and the preparedness and adaptive ability of communities, on the potential loss of functionality of buildings. The probabilistic evaluation of these effects would enhance FEMA P-58's overall capability to assess seismic performance and estimate building risk.

CONCLUSIONS

This reconnaissance-based study provides valuable insights into the correlation between earthquake-induced building damage and its functionality post-event, as well as other impeding and/or resilience factors that influence these correlations. The end-to-end outcomes of the FEMA P-58 methodology were benchmarked against empirical and observed building data from the Hualien Earthquake. The benchmarking results demonstrate FEMA P-58's ability to leverage information about building properties and ground motions to predict seismic performance. Where misalignment existed between the predicted performance and observed data, impeding factors played out, including effects of the building site or neighbouring buildings, the design and quality of acceleration-sensitive non-structural components, and the resilience of building tenants. In Hualien's case, preparedness and adaptive measures adopted by residents appeared to have played a major role in maintaining the continued use of buildings that were damaged but safe to occupy.

For buildings with red placards, FEMA P-58 predictions were generally consistent with observed data. Some data on the type and construction era of non-structural components, as well as whether they have proper anchorage or comply with existing design standards, are needed to better estimate repair times and costs for buildings with yellow or green placards.

Another key factor in maintaining building functionality across all buildings with yellow- and green placards was the high serviceability of utilities. This was largely attributed to the swift restoration of earthquake-damaged infrastructure that provides utility services. Localised damage to pipes on the building premises was also rapidly repaired without disrupting building functionality. As shown in studies by Shegay et al. (2025) [36] and Lee et al. (2025) [30], changes to the building code and regulations after the Chi-Chi Earthquake in 1999, and subsequent retrofit programmes for residential buildings, also contributed to the resilient performance of retrofitted buildings.

The benchmarking of the FEMA P-58 framework against empirical data from Hualien highlighted the importance of a reconnaissance trip for collecting functional recovery data, in addition to a conventional reconnaissance focused mainly on damage lessons. The functional recovery data and lessons learned from Hualien, in particular the positive effects of retrofit programmes on the resilient performance of buildings that had been retrofitted, would support the ongoing development of low-damage seismic design guidelines and design practice in NZ that could lead to enhanced seismic performance and recovery of buildings.

ACKNOWLEDGMENTS

The authors are extremely thankful to the Taiwanese agencies that kindly gave up their time to assist the NZSEE delegation. These include:

- Hualien County Government
- Hualien Emergency Operations Centre and Hualien Fire Department
- Hualien Architects Association
- Taroko National Park Headquarters, National Park Service, Ministry of the Interior
- NCREE of the NIAR
- National Science and Technology Centre for Disaster Reduction (NCDR)
- Office of Disaster Management, Executive Yuan
- Taiwan Residential Earthquake Insurance Fund (TREIF)
- National Fire Agency, Ministry of Interior
- Highway Bureau, Ministry of Transportation and Communications
- Central Weather Administration, Ministry of Transportation and Communications
- Agency of Rural Development and Soil and Water Conservation (ARDSWC)
- Tzu Chi Hospital and Foundation
- Hotel Les Champs Hualien
- Hualien Hotel Association
- All the building owners, residents, body corporates, and professionals who assisted us and provided valuable building information during our visits.

In particular, the authors are extremely grateful to Yu-Chen Ou (Director General) for providing support and to Jui-Liang Lin (Building Engineering Division Director), Ming-Chieh Chuang (Associate Researcher), Kai-Ning Chi (Associate Researcher), Gee-Jin Yu (Associate Technologist) and Bai-Yi Huang (Assistant Researcher) of the NCREE of the NIAR for their great efforts in assisting with data collection. The NZSEE team would like to acknowledge the joint building inspections and collaboration with other teams. These included NZ researchers funded by the Royal Society of New Zealand; Japanese experts; other NCREE professors and researchers; and EERI members from the USA and Indonesia.

The authors are grateful to Professor Jack Baker, Professor Curt Haselton, and the SP3 team for providing an academic license for SP3 (https://www.hbrisk.com) for FEMA P-58 benchmarking analyses. Calculations and case studies of individual buildings were performed by research assistant Kasra Habiti, PhD student at the University of Auckland, funded by QuakeCoRE, Te Hiranga Rū QuakeCoRE, New Zealand Centre for Earthquake Resilience.

The team would also like to acknowledge Ken Elwood for his input into the development of the building functional recovery survey and Gregory MacRae for reviewing this manuscript. The team would like to thank two anonymous reviewers for their comments and suggestions that significantly improved the manuscript.

Lastly, the NZSEE would like to acknowledge the Natural Hazards Commission – Toka Tū Ake's ongoing support for NZSEE's Learning from Earthquakes (LFE) programme.

DATA AVAILABILITY STATEMENT

The building functional recovery form developed for this study, along with the data collected from each building, is available on DesignSafe.

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