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Seismic Damage Characteristics and Mitigation Strategies in Southern Sichuan Basin, China

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Abstract

In recent years, seismic activity in the southern Sichuan region has increased significantly. Frequent moderate-to-strong earthquakes have caused severe building damage, casualties, and substantial economic losses, making regional seismic risk increasingly prominent. Based on historical seismic catalogs, geological settings, macroseismic intensity data, and strong motion records, this study systematically analyzes regional seismicity, spatial distribution, and strong ground motion characteristics, and quantitatively investigates the distribution and variation of seismic intensity. It further explores the impacts of earthquakes on various building structures, geological disaster chains, lifeline engineering, and human safety, as well as the underlying damage mechanisms. Finally, targeting the widely existing brick masonry structures, this paper proposes cost-effective and easy-to-implement seismic reinforcement measures combined with typical failure modes and casualty causes. The results provide a scientific basis for seismic disaster prevention planning, engineering seismic practice, and risk management in southern Sichuan and comparable regions.

Keywords: southern Sichuan; ground motion intensity; earthquake disaster; rural masonry retrofitting

1. Introduction

Earthquakes are the most destructive natural disaster, posing severe threats to human life, property, and the stable development of society and the economy. Although Sichuan Province is located in a high-seismicity zone in western China, its eastern region lies within the stable Yangtze Block, where historically moderate-to-strong earthquake activity has been relatively weak. In particular, the southeastern part of Sichuan has long been considered a region of low seismic activity. Consequently, the seismic fortification standards in this area have generally been at moderate to low levels, with basic design intensities ranging from VI to VII on the seismic intensity scale [1]. In both urban and rural areas, especially in vast rural regions, brick masonry buildings and older brick-wood buildings, which are forms of construction with relatively poor seismic performance, have been widely adopted. From the perspective of regional seismic safety planning, in areas with infrequent, low-intensity earthquakes, aligning building seismic resistance with actual seismic risk is a reasonable and cost-effective technical strategy. In other words, the seismic fortification objectives for buildings should not be set to blindly pursue excessively high standards; rather, they should be scientifically established based on the characteristics of the regional seismic environment to achieve an optimal balance between safety and resource allocation. Therefore, the historically low seismic capacity of buildings in southern Sichuan can be regarded as reasonable and grounded in the local context.

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Recently, seismic activity in southern Sichuan has increased notably in both frequency and magnitude, primarily driven by anthropogenic industrial activities [2]. A series of notable earthquakes has occurred, exemplified by the Ms 6.0 earthquakes in Changning in 2019 and in Luxian in 2021, which caused widespread social impacts and substantial material losses. These events signify a major shift in the region's seismic risk characteristics. Consequently, the area has transformed from a region with relatively stable seismic risk into one characterized by dynamically changing risk, thereby posing unprecedented challenges to traditional disaster prevention and mitigation systems. Against this backdrop, a systematic review and analysis of the seismic hazard characteristics in southern Sichuan is urgently needed to accurately assess current earthquake risks and formulate targeted disaster prevention and mitigation strategies.

Field investigations of earthquake damage are among the most direct and reliable research methods for elucidating the mechanisms of structural seismic damage and assessing the seismic performance of regional buildings. These investigations play an irreplaceable and crucial role in post-earthquake safety assessments and scientific research, with the collected damage data serving as the fundamental basis for developing targeted engineering reinforcement measures and regional disaster prevention and mitigation strategies [3]. The earthquake that struck L'Aquila on 6 April 2009, underscored the significant vulnerability of churches. Lagomarsino [4] conducted damage assessments of over 700 churches to identify collapse mechanisms across various architectural components. Subsequently, Longobardi et al. [5] investigated 23 churches affected by the 2012 Emilia-Romagna earthquake in Italy. They compared actual seismic damage with three distinct methods: simplified mechanical models, the observations documented in the AeDES form, and dynamic analysis. This comparison aimed to evaluate the reliability of these methods for rapidly estimating the degree of seismic damage in churches. On 25 April 2015, a Mw 8.1 earthquake struck near Pokhara, Nepal. Liu et al. [6] conducted an in-depth investigation into the seismic damage of various engineering structures in Nepal, where they analyzed seismic damage in typical frame and masonry buildings, including the causes of that damage. Recommendations for strengthening measures and suggestions for post-earthquake reconstruction were also provided. On 24 January 2020, a Mw 6.8 earthquake occurred in the Sivrice district of Elazığ Province, Turkey, resulting in the collapse or severe damage of numerous buildings. Caglar et al. [7] studied the structural damage in different building types and identified several structural deficiencies and errors. On 12 November 2017, a Mw 7.3 earthquake struck the city of Sarpol-e Zahab in Iran. Khanmohammadi et al. [3] conducted a comprehensive and detailed investigation of more than 81 damaged steel structures and reinforced concrete buildings. The study provided an extensive explanation of various structural and non-structural damage and classified the buildings into five damage states based on the severity, extent, and type of steel structure damage, as well as the observed residual drift. A new damage index was also proposed. On 23 November 2022, a Mw 5.9 earthquake struck Düzce-Gölyaka in northwestern Turkey, severely damaging or destroying numerous buildings in rural areas. The damage sustained by masonry structures was classified and evaluated by Dedeoğlu et al. [8]. Based on the damage categories identified within the study area, reinforcement techniques were proposed to improve the seismic performance of existing brick-concrete buildings with low resistance. On 6 February 2023, two strong earthquakes with Mw 7.7 and Mw 7.6 occurred in Kahramanmaraş, Turkey, resulting in widespread building collapse and damage, and causing more than 50,000 fatalities. Damcı et al. [9] conducted extensive field reconnaissance and observations in the affected areas immediately following the earthquakes. Detailed damage assessments were performed for various structural types in consideration of the recorded ground motions. Although peak ground accelerations exceeding the design limits were recorded at certain locations, pervasive structural deficiencies were identified as the primary cause of collapse and damage, a finding further corroborated by the field investigations of Avğın et al. [10]. Similarly, Kırtel et al. [11] focused on the damage characteristics and underlying causes in industrial buildings with different support systems. It was emphasized that improving the quality of construction materials, ensuring compliance with steel reinforcement ductility requirements, and implementing strict quality control during the production phase are urgent measures for reducing seismic risk. Subsequently, Toprak et al. [12] and Akinci et al. [13] also analyzed the causes of structural damage, the influence of high acceleration values, surface deformations, and lifeline system performance. On 5 September 2022, a Ms 6.8 earthquake struck Luding County in Sichuan Province, China. Bai et al. [14] examined seven base-isolated buildings in the affected areas, providing detailed descriptions of the damage levels and investigating the factors influencing the observed performance. Recommendations were proposed to address the pressing challenges in the development and application of base-isolation techniques for building structures.

With the transformation of southern Sichuan from a region with historically low seismicity to one frequently affected by moderate to strong earthquakes, the area has rapidly emerged as a focal point for research in both geological and engineering disciplines. Several key findings have been accumulated through the study of multiple representative seismic events. Existing research can be categorized into two main directions. The first focuses on investigating earthquake-generating mechanisms. Geologists have employed techniques such as focal mechanism solution analysis and relocated aftershock sequences to elucidate the intrinsic links between industrial activities and fault activation. These efforts aim to reassess the upper limits of regional seismic hazard and refine existing conceptual models. The second direction emphasizes the analysis of building seismic damage. Engineers have conducted systematic post-earthquake damage surveys to examine the characteristics and vulnerabilities of various structural types. The findings provide essential evidence for evaluating regional seismic performance and the resilience of the built environment. For instance, following the Junlian Ms4.9 earthquake of 28 January 2017, Xiao et al. [15] conducted a preliminary analysis of the regional geological environment, focal mechanism solutions, and aftershock sequences to explore the distribution characteristics of seismic damage and the underlying damage mechanisms. Then, they summarized the seismic damage characteristics of various building types in the affected area and found that most buildings were masonry structures with severe damage. Based on a post-earthquake damage survey following the 17 June 2019 Changning Ms 6.0 earthquake, Yang et al. [16] observed that buildings that were designed and constructed to meet code standards typically sustained little to no damage to their primary structural members under seismic loading. However, non-structural components such as infill walls and ceilings exhibited significant damage, which contributed to the loss of the building's functionality. Furthermore, structural measures significantly improved the seismic performance of brick-concrete residential buildings; the presence of tie beams and structural columns was found to greatly reduce seismic damage. This issue was also formally addressed by Pan et al. [17] in their survey, finding that masonry structures, owing to a lack of proper seismic design and effective seismic-resistant measures, suffered the most severe damage in this earthquake, making them the primary cause of casualties. After the 16 September 2021, Ms 6.0 earthquake in Luxian, Pan et al. [18] conducted a detailed seismic damage survey of buildings in the affected villages and towns. They summarized the typical seismic damage characteristics of brick-wood, masonry, and reinforced concrete frame structures, revealing that the proportion of severe damage to brick-wood structures was four times that in frame structures. Additionally, the number of collapsed brick-wood structures was seven times higher than that of masonry structures, while no collapses were observed in frame structures.

Numerous studies have examined earthquake damage to buildings in southern Sichuan, but these analyses typically focus on individual seismic events or provide in-depth investigations of specific structural types. There is a lack of systematic integration of common seismic damage patterns, failure mechanisms, and their roles within the entire disaster chain across multiple earthquakes at a regional scale. Furthermore, the proposed disaster mitigation and reinforcement measures are often generalized and lack practical, actionable solutions. As a result, current research does not provide a comprehensive framework for optimizing disaster prevention strategies in the face of new seismic risks. This paper systematically investigates the seismic characteristics, damage patterns, and mitigation strategies for the southern Sichuan region. The study begins by analyzing the characteristics of regional seismicity and strong ground motion, elucidating their dynamic effects on engineering structures. A comparative analysis between the findings and the current seismic design code reveals that the code provisions for both the basic seismic intensity and the vertical peak ground acceleration are non-conservative, with insufficient safety margins. Meanwhile, the paper focuses on the seismic performance and failure mechanisms of typical building typologies, specifically brick masonry and brick-wood structures, identifies the mechanical weak links of each structural type, and thus provides a basis for subsequent seismic retrofitting strategies. It further explores the impacts of seismic geological hazards, damage characteristics of lifeline infrastructure systems, and the disaster models related to casualties. This further clarifies the local disaster characteristics and helps identify the priority tasks for current risk prevention efforts. Finally, through a systematic analysis of the seismic damage chain, this paper proposes seismic reinforcement strategies and regional resilience-based disaster prevention plans for existing buildings in southern Sichuan, taking into account structural vulnerability, key factors for human safety, and economic feasibility. These measures provide scientific foundations and practical support for enhancing the region's seismic disaster prevention and resilience capabilities.

2. Seismicity and Intensity Characteristics

2.1. Geographic Location and Seismicity

Figure 1 presents the geographic location and seismicity analysis of the study region. The region is located in southern Sichuan Province in southwestern China, bordering three other provinces (Figure 1a). The terrain is predominantly plains and hills, with elevations gradually increasing from north to south. Notably, only one major active fault exists within this area. Seismicity within the region exhibits pronounced spatial clustering, with the highest concentration of earthquakes in the magnitude range of 3.0–3.9 (Figure 1b). This distribution is closely linked to both the regional tectonic setting and anthropogenic engineering activities. Based on seismic monitoring data spanning the past three decades (https://data.earthquake.cn accessed on 19 June 2026)), the number of earthquakes of magnitude ≥ 3.0 has showed a continuous upward trend from 2007 onward, peaking in 2019 and then gradually decreasing (Figure 1c). The cumulative frequency curve for $M \geq 3.0$ shows a steady accumulation of seismic events, with approximately 1646 earthquakes over the past 35 years, most of which occurred after 2015, indicating a notable increase in seismic activity during this period. From an engineering perspective, the potential risk posed by moderate-to-strong earthquakes is of particular concern, as these events could cause significant damage to buildings and infrastructure. Thus, a further analysis was conducted focusing on earthquakes of magnitude ≥ 4.0. The results indicate that although earthquakes in the 3.0–3.9 magnitude range dominate in frequency, $M \geq 4.0$ events should not be overlooked. The seismic sequence shows that before 2000, earthquakes with magnitudes greater than 4.0 were infrequent. Between 2000 and 2010, the frequency of these events increased gradually, although most remained below magnitude 4.5, with only two events of magnitude 5.1 recorded. However, after 2010, the number of earthquakes with magnitude ≥4.0 increased significantly, exhibiting distinct spatial clustering patterns. Particularly notable is the marked increase in earthquakes of magnitude 5.0 and above, with the largest event reaching Ms 6.0, surpassing the region's historical upper limit. Concurrently, the annual occurrence rate of moderate-to-strong earthquakes has risen considerably. Regarding focal depth distribution, seismic events prior to 2007 were primarily concentrated within the 0–40 km depth range, with a relatively dispersed pattern. In contrast, recent seismic activity has concentrated at shallower depths, primarily within the upper crust, below 10 km (Figure 1d). The shallow-source nature of larger earthquakes is particularly pronounced [19,20], further emphasizing the increased threat posed by seismic activity to surface engineering structures.

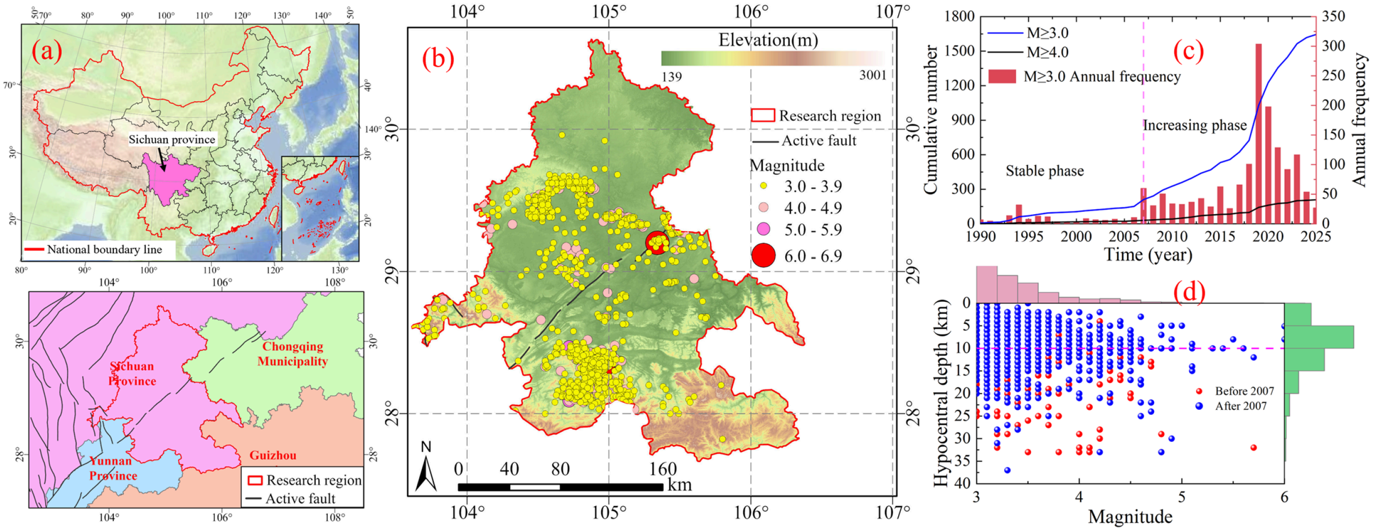

Figure 1. Geographic location and seismicity analysis of the research region. (**a**) Geographic location; (**b**) spatial distribution of earthquakes; (**c**) cumulative seismic time-series curve; (**d**) magnitude-source depth distribution characteristics.

In summary, seismicity in southern Sichuan follows the magnitude–frequency decay law. Although small earthquakes dominate in number, moderate-to-strong earthquakes have become more frequent, stronger, and shallower in recent years, establishing a clear trend in regional seismic behavior. These characteristics provide critical data for regional seismic hazard assessments and the design of engineering structures resistant to seismic activity.

2.2. Macroseismic Intensity Distribution

Macroseismic intensity provides a direct reflection of ground motion strength and post-earthquake damage distribution, demonstrating a wide range of applications in China, including seismic design, disaster assessment, and emergency response. Following each significant earthquake, seismic departments conduct macroseismic intensity surveys and develop corresponding intensity maps to accurately depict the spatial distribution of seismic impacts. Figure 2 presents a comprehensive isoseismal map of the southern Sichuan region, generated by compiling all historical earthquakes with magnitudes greater than 5.0. The highest recorded macroseismic intensity is VIII, caused by the Ms 6.0 earthquakes in Changning and Luxian, whereas most earthquakes in the area have resulted in an intensity of VI. It is important to note that smaller earthquakes, with magnitudes ranging from 4 to 5, frequently occur outside the intensity VI range. Although the impact area of these lower-magnitude events is limited, they have not undergone specialized surveys, and intensity maps have not been developed for them. However, due to their high frequency and widespread distribution, these smaller earthquakes could potentially lead to an underestimation of the current extent of the VI intensity zone. In addition to local impacts from earthquakes, strong distant earthquakes in Sichuan can also affect this area. For instance, although the southern Sichuan region was located up to 200 km from the epicenter of the 2008 Wenchuan Ms 8.0 earthquake, long-period seismic waves and intense ground shaking still imposed significant effects at such distances. As indicated by the isoseismic lines, the intensity in this area during that event was VI.

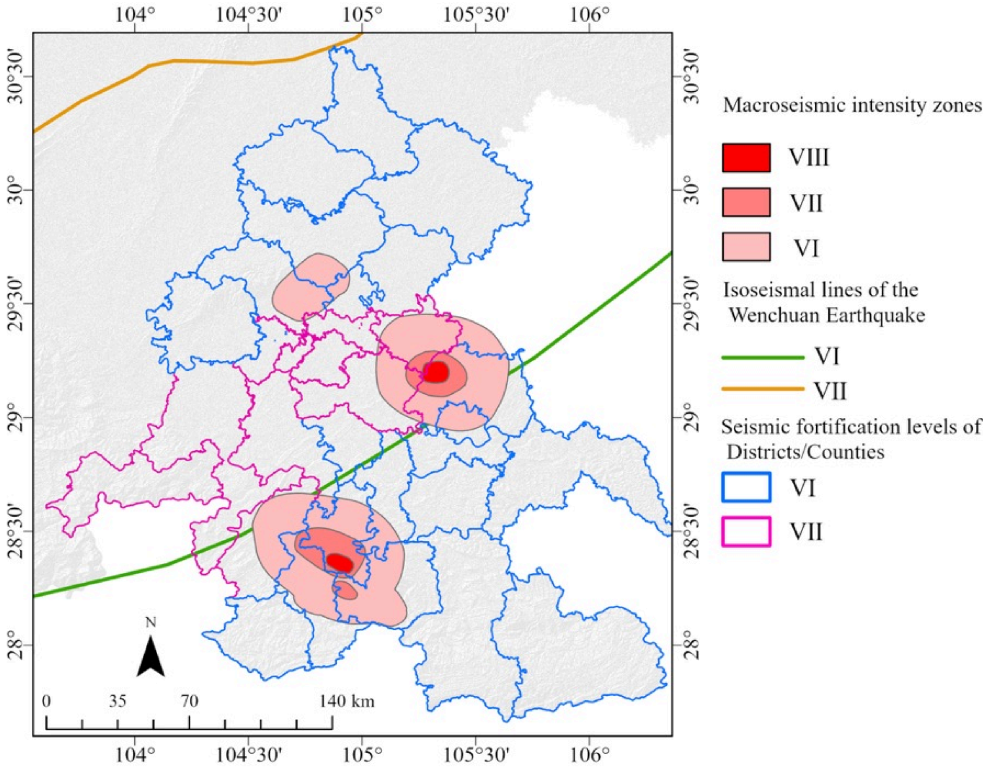

Figure 2. Distribution of macroseismic intensity effects and the basic fortification intensity for each county.

A further comparison with the currently adopted basic seismic design intensity for the region, defined by a 10% probability of exceedance over 50 years, reveals that areas originally classified with a seismic design level of VI have experienced peak seismic intensities of VII or VIII during multiple seismic events, which are significantly higher than the prescribed safety level. According to the definitions of seismic fortification intensity at different probability levels provided in current seismic design codes [21], frequent earthquakes corresponding to a 63% exceedance probability over 50 years have an intensity approximately 1.55 levels below the basic design intensity, while rare earthquakes with a 2% exceedance probability over 50 years have an intensity roughly one level above the basic design intensity. Consequently, the maximum intensities induced by recent earthquakes, along with their occurrence frequency, have significantly surpassed the originally established seismic design levels for the area. This indicates that the current design standards may be insufficient to address the region's actual seismic activity characteristics. Therefore, it is essential to conduct a scientific review and appropriate enhancement of the regional seismic design levels based on the latest seismic hazard analysis results.

2.3. Strong Ground Motion Characteristics

2.3.1. Response Spectrum

According to the China Earthquake Intensity Scale (GB/T 17742-2008) [22], the peak ground acceleration (PGA) range for macroseismic intensity zone V, where damage is negligible, is 22–44 gal, while that for intensity zone VI, where damage begins to occur, is 45–89 gal. Thus, approximately 40 gal represents a critical threshold marking the transition from undamaged to visible structural damage. To investigate the seismic characteristics that may cause engineering damage, this study selected ground motion records from several seismic events in southern Sichuan with PGA values exceeding 40 gal. Based on the selected records, a systematic analysis of their acceleration response spectra was conducted. Figure 3 presents a comparison of the horizontal and vertical acceleration response spectra with a damping ratio of 5% from selected typical strong motion records and the design spectra for seismic design levels VI and VII outlined in China's "Code for Seismic Design of Buildings" [23]. The horizontal response spectrum is derived from the maximum values of the north–south and east–west records. The analysis indicates that most recorded acceleration response spectra peaked between the design spectra for seismic effect coefficients of levels VI and VII, indicating that they generally exceed the level VI design standards but do not typically reach the level VII standards. Although certain records exhibit response spectrum values significantly exceeding the level VII design spectrum in the short-period range, such occurrences are rare and are likely attributable to localized site effects that amplify ground motion records, rather than constituting a widespread trend in the region. It is noteworthy that due to limitations in the distribution of recording stations and the number of records, particularly in near-fault areas, the coverage and representativeness of strong motion records remain insufficient. This shortfall may impact the comprehensive understanding of near-fault seismic characteristics. Additionally, the response spectra of the selected records generally displayed a rapid decay trend after periods exceeding 1 s. In this long-period range, most spectra fell below the design spectrum values. This reflects a spectral characteristic of moderate to strong ground motions in southern Sichuan, which are rich in high-frequency components but relatively weak in long-period components. This finding suggests that seismic actions on mid- to long-period structures, such as high-rise buildings, may be lower than those anticipated by the design standards. Conversely, for low- to mid-rise buildings, such as those characterized by short periods, the concentration of seismic energy in the high-frequency range could mean that the actual seismic forces experienced may approach or even exceed the design values, making them more susceptible to damage.

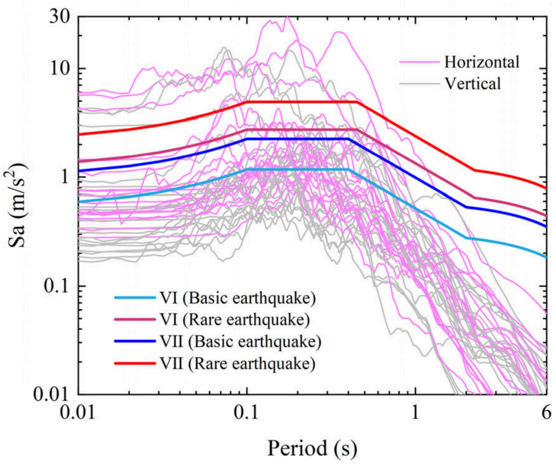

Figure 3. Comparison between horizontal and vertical acceleration response spectra with a 5% damping ratio and the standard design spectra.

2.3.2. Amplitude

Amplitude is a critical parameter for assessing the intensity of ground motion, as it directly reflects the amount of energy carried by seismic waves. Figure 4a summarizes the distribution characteristics of horizontal and vertical PGA from over eighty sets of seismic records. The results indicate that among earthquake records capable of causing significant damage to engineered structures, approximately 29.24% of the samples exhibited vertical PGAs exceeding 2/3 of the horizontal PGA threshold established by the current Code for Seismic Design of Buildings [23]. This proportion suggests that the intensity of vertical ground motion components is non-negligible in a considerable number of strong seismic events and exceeds the regulatory limits. This indicates that the current seismic design standards may be overly conservative in accounting for vertical seismic forces, leading to an underestimation of their impact on the safety performance of building structures, particularly in vertical components and cantilevered sections. Consequently, it is essential to re-evaluate the basis for vertical ground motion parameter values in subsequent revisions of the standards to enhance the overall resilience and safety of engineering structures during extreme seismic events. Figure 4b illustrates the logarithmic linear relationship between peak ground acceleration and peak ground velocity, where both PGA and PGV are calculated as the geometric mean of the east–west and north–south horizontal components. Based on the correlation between horizontal ground motion parameters and seismic intensity outlined in the Chinese Seismic Intensity Scale (GB/T 17742 2008) [22], PGA-based intensity levels are generally higher than PGV-based levels in this region. Specifically, during the same seismic event, when PGA reaches a certain threshold, the corresponding PGV often falls below the typical PGV range for that intensity level. This phenomenon is closely related to the source characteristics of moderate earthquakes (typically magnitude 5.0–6.0) in southern Sichuan. Due to their relatively low magnitudes, these earthquakes are characterized by short rupture durations and limited rupture dimensions, resulting in a more concentrated energy release. As a result, the high-frequency components dominate the ground motion spectrum, while the medium- and low-frequency components remain relatively weak. Consequently, ground motions in this region exhibit a typical pattern of high PGA and low PGV, highlighting the controlling influence of both source mechanisms and propagation paths on the spectral characteristics of seismic ground motions. Figure 4c presents the relationship between PGA and the equivalent predominant frequency, where the equivalent predominant frequency of seismic records is defined as PGA/(2πPGV). The equivalent predominant frequency is an important parameter for evaluating the characteristics of seismic motion spectra and their relationship with structural damage potential [24,25]. In their simulation of earthquake damage to buildings in Luxian County, Pan et al. [26] proposed that different structural types exhibit significantly varying ranges of natural vibration periods: traditional brick-wood structures generally fall within the range of 0.2 to 0.4 s, brick-mixed structures range from 0.1 to 0.36 s, while frame structures present a broader distribution from 0.2 to 1.8 s. Consequently, from the perspective of spectral matching, masonry structures, with their wide range of natural frequencies, are more likely to resonate with the common high PGA components present in seismic motion, thus exacerbating damage. The principal period range of brick-wood structures also corresponds with several high-energy frequency bands, indicating a similarly high vulnerability to seismic impacts. In contrast, the fundamental frequencies of frame structures are typically lower, allowing them to somewhat avoid the high-frequency dominant components of seismic motion, thereby mitigating the effects of resonance.

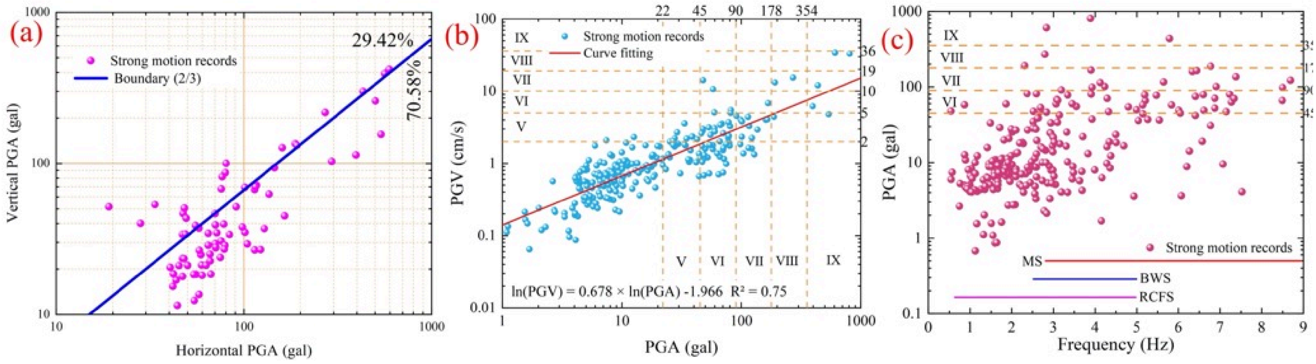

Figure 4. Characteristics of ground motion amplitudes. (**a**) Vertical and horizontal PGA value distribution and code threshold comparison. (**b**) Log-linear relationship between PGA and PGV. (**c**) Corresponding relationship between PGA and equivalent predominant frequency.

2.3.3. Duration

Duration has been recognized as an indispensable seismic parameter in the earthquake-resistant design and research of engineering structures. This study focuses on the definition of duration currently prevalent within the engineering community, specifically, effective duration. Effective duration is typically based on the Arias intensity time history and is defined as the time interval required for the cumulative Arias intensity to reach 5% to 75% or 5% to 95% of the total intensity. Since this definition is expressed as a percentage range relative to the total energy of the seismic motion, it is also referred to as relative duration. Figure 5 illustrates the relationship between seismic motion relative duration, peak ground acceleration, and epicentral distance. Within the epicentral distance of 40 km, which roughly corresponds to the maximum distance from the epicenter to the boundary of the intensity VI zone for a Ms 6.0 earthquake, the effective duration of seismic motion is generally quite short, seldom exceeding 10 s. Notably, the duration is shorter near the epicenter, with values within 20 km of the epicenter often under 5 s. This phenomenon reflects the characteristics of near-field seismic motions, which are typically associated with rich high-frequency content, concentrated energy release, and rapid rupture processes. These attributes may be related to the high rupture speed and short rise time of the seismic source. In regions where the epicentral distance exceeds 40 km, the duration of seismic motion is more variable. Some records show short durations at PGA values below 20 gal, while others show relatively longer durations at PGAs between 20 and 40 gal. This variability may be attributed to local soil conditions, topographic scattering, and the superposition of seismic waves along the propagation path, indicating significant modulation of mid-to-far field seismic motion by these effects. From an engineering perspective, a shorter duration typically indicates that seismic energy is released over a brief period. This may lead to higher instantaneous responses; however, given the limited accumulation of input energy, overall damage to structures capable of dissipating energy, such as reinforced concrete frames and shear wall structures, may be relatively minor. Conversely, for brittle structures or non-structural components, short-duration, high-intensity pulses can still induce severe localized damage.

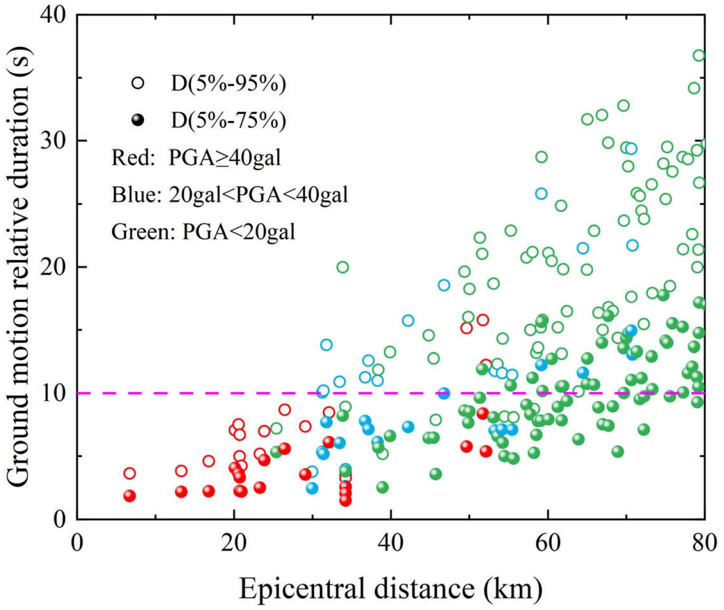

Figure 5. Relationship of relative ground motion duration with PGA and epicentral distance.

3. Damage Analysis of Typical Building Structures

After every destructive earthquake, the Sichuan Earthquake Agency promptly dispatches specialized earthquake engineering personnel to form a field investigation team. This team is tasked with conducting damage assessments and evaluating macroseismic intensity in the impacted areas. The authors' team has actively participated in this mission multiple times, adhering strictly to the relevant technical guidelines. Detailed damage assessments were performed, with a particular focus on typical building structural types within the study area. A summary of the basic information for each typology is presented in Table 1. The various seismic damage phenomena observed at the site are described in detail below.

Table 1. Typical building typologies and characteristics.

Buildings Typology	Materials	Typical Age	Number of Stories	Seismic Details	Typical Examples/Usage
Reinforced concrete structures	Load-bearing: cast-in situ reinforced concrete; Non-load-bearing: clay brick.	1980s–	3–10	Fully complies with seismic design codes (e.g., seismic joints, strong-column/weak-beam design).	Residential or commercial buildings; schools.
Brick masonry structures	Vertical: clay bricks, cement mortar; Horizontal: reinforced concrete slabs.	1960s–	1–7	Tie columns, ring beams; Older ones lack detailing.	Residential buildings.
Brick-wood structures	Vertical: clay bricks, lime/cement mortar; Horizontal: timber beams.	–1990s	1–2	No seismic detailing: structural integrity relies on mortise-tenon joints and iron nails.	Traditional vernacular buildings.
Rammed earth structures	Vertical: compacted earth. Horizontal: timber beams	–1980s	1	No seismic detailing: relying solely on the cohesion of the soil.	Abandoned dwellings.

3.1. Reinforced Concrete Structures

Reinforced concrete structures experience relatively less overall damage during earthquakes. Among the damaged buildings, mid-and low-rise frame structures are predominant, while high-rise buildings such as shear wall structures and frame-shear wall structures are less commonly affected. This is primarily because high-rise residential buildings are typically located in urban areas, which are farther from the epicenter, and the energy carried by long-period seismic waves is relatively low there. Furthermore, these structures exhibit excellent seismic resistance, resulting in few instances of damage. Damage to such buildings has only been observed in a few instances, such as during the Ms 6.0 earthquake in Changning.

3.1.1. Beam-Column Joint Damage

Because the maximum earthquake magnitude in the southern Sichuan region did not exceed Ms 6.0, strong ground shaking was observed only locally in small areas. Consequently, the number of collected cases of beam-column joint damage was limited, and the overall seismic damage was relatively mild. However, in school buildings, a particular frame structure with a distinctive layout exhibited significant damage to its columns. The typical feature of such buildings lies in the arrangement of the main frame and infill walls (Figure 6a,b). Along the short-axis direction of the structure, the column lines are often asymmetrically arranged over two spans: one span is relatively large and functions as a classroom, while the other span is smaller and serves as a corridor. In the corridor area, the ground floor is usually free of enclosing walls, creating a relatively open space. In contrast, the upper floors are equipped with walls approximately 1.2 m high, which also serve as railings. On the sides of the classrooms, conventional-height infill walls are provided, with openings incorporated for doors and windows. This asymmetric arrangement of infill walls leads to significant differences in the constraint conditions of columns at various locations, which in turn results in markedly different actual stress states. As a consequence, the frame columns at the front remain undamaged, while the infill walls suffer extensive damage (Figure 6c). Conversely, the walls at the rear remain intact, but shear diagonal cracks appear in the frame columns (Figure 6d). The mechanical behavior of columns in different positions within this structural configuration has been extensively investigated in recent years [27–29]. Both shaking table experiments and in situ monitoring of existing buildings have shown that under seismic action, shear forces are highly concentrated in columns constrained by infill walls. The shear forces experienced by these columns can reach three to five times those of columns without infill wall constraints. Regarding mechanical performance, columns without infill wall constraints exhibit lower load-bearing capacity but demonstrate greater deformation ability and ductility; conversely, columns constrained by infill walls possess higher stiffness and load-bearing capacity, while their deformation capacity and ductility are relatively limited. It is noteworthy that when constrained columns are damaged, the structure has often already begun to deteriorate and may even be at risk of collapse. At this stage, unconstrained components typically have not reached their ultimate displacement, and their actual ductility may be lower than that of the constrained columns. This phenomenon indicates that unreasonable structural layouts and internal force distributions prevent effective collaborative action among components, thereby restricting the full utilization of material properties. In summary, even under moderate-intensity earthquakes, irregularities in structural configuration can remain a critical factor affecting seismic performance. Therefore, buildings of this structural type should receive careful consideration. Measures such as the installation of dampers are recommended to improve the structural stress response and adjust the internal force distribution, thereby preventing structural damage and protecting the safety of students and staff.

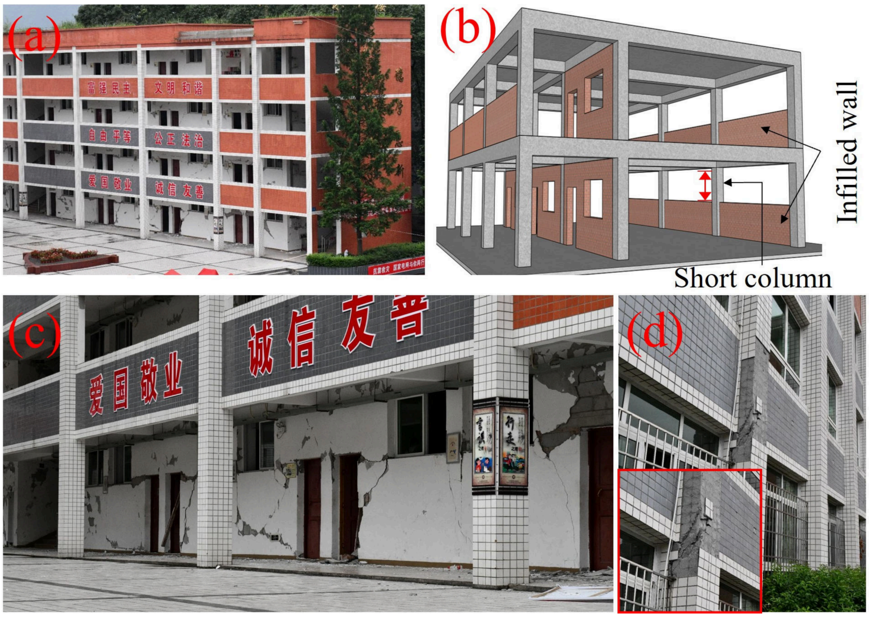

Figure 6. Construction forms and damage characteristics of a typical frame structure. (**a**) Overall exterior view of the building. (**b**) Schematic layout of internal longitudinal beams, columns, and walls. (**c**) Infill wall damage on the front elevation. (**d**) Column shear failure on the rear elevation.

3.1.2. Infill Wall Damage

In frame structures, the failure of infill walls is often more common than that of beam-column joints. When the seismic intensity is low, cracks tend to form at the junctions between infill walls and the frame beams and columns (Figure 7a). These interfaces typically rely solely on mortar for connection, which has a low bond strength and is prone to separation under structural deformation. Additionally, infill walls often exhibit diagonal cracks or form intersecting fine cracks due to repeated seismic actions (Figure 7b). As non-load-bearing components, most infill walls are constructed with hollow bricks to control construction costs. These materials are brittle and weak, making them prone to crushing during strong seismic motions. Once a porous brick wall cracks, its stiffness rapidly decreases, leading to poor deformation capacity. Initial cracks tend to expand quickly, resulting in a higher risk of wall instability or even collapse (Figure 7c). In contrast, solid brick infill walls, with higher compressive and shear strengths, exhibit better overall integrity and can more effectively resist seismic forces, resulting in relatively less severe damage (Figure 7d). However, the stronger overall integrity of solid brick walls may have an adverse effect: their restraining effect on the frame beams limits beam deformation, obstructing the formation of the strong column-weak beam mechanism, potentially causing brittle shear failure of the frame columns. Another common issue is the improper design of door and window openings, leading to short-column effects around the openings, which can result in shear failure during an earthquake (Figure 7e). Compared to frame structures, the seismic damage in high-rise shear wall structures is generally less severe, with fewer instances of damage. Fine cracks may form at the junctions between the infill walls and beams or columns, but the walls typically do not suffer severe damage, usually only showing the detachment of exterior finishes such as tiles (Figure 7f).

Figure 7. Failure modes of infill walls. (**a**) Minor cracks at wall-frame interface. (**b**) Internal cracks in infill wall. (**c**) Damage of infill wall with porous shale bricks. (**d**) Damage of infill wall with solid bricks. (**e**) Short column failure. (**f**) Cracks at wall–frame interface in shear wall structure.

3.2. Brick Masonry Structures

Brick masonry structures are the most widespread type of building in southern Sichuan, found in both rural and urban areas. However, significant differences exist in the seismic performance and failure modes of masonry structures in urban and rural areas, influenced by construction standards, economic conditions, and technological levels. In urban areas, masonry structures are predominantly reinforced, with horizontal tie bars, tie columns, and ring beams incorporated into the walls. This configuration significantly enhances their integrity and ductility, providing them with strong seismic resistance. In contrast, rural areas typically employ unreinforced brick masonry structures. These buildings are often constructed by local craftsmen based on experience, lacking formal design and seismic-resistant measures. The brick masonry materials used have low strength, and the mortar bond is weak, leading to poor overall structural integrity and limited deformation capacity. As a result, under the same seismic forces, reinforced masonry buildings in urban areas generally sustain less damage. In contrast, unreinforced masonry buildings in rural areas tend to exhibit more complex and severe failure modes, making them the primary type of construction responsible for earthquake damage and casualties.

3.2.1. Wall Damage

As critical components of masonry structures, walls bear all vertical and horizontal loads. Under seismic forces, the failure modes of these walls are complex and varied, often exhibiting the most severe damage. In areas with larger openings, such as doors and windows, sudden changes in cross-section and stiffness discontinuities tend to create significant stress concentrations, leading to diagonal cracks (Figure 8a,b). These cracks are common even in low-intensity seismic zones, such as those with a seismic intensity of VI. The damage to the main load-bearing walls is progressive: in the initial stages, it typically manifests as slight diagonal cracks on the interior wall surfaces (Figure 8c). As the seismic forces persist, these cracks rapidly expand, eventually traversing the entire wall (Figure 8d). When seismic intensity is high, crack widths increase significantly, causing a dramatic reduction in the wall's load-bearing capacity and ultimately leading to a complete loss of its structural function. Moreover, under repeated seismic actions, the walls often develop intersecting diagonal cracks (Figure 8e). The formation mechanisms of unidirectional diagonal cracks and bidirectional intersecting cracks are closely related to the seismic event's progression. Typically, unidirectional diagonal cracks appear when the wall first experiences seismic forces, compromising its overall integrity. If subsequent seismic forces are not strong, or if the wall damage is so severe that it can no longer transfer loads, bidirectional intersecting cracks may not develop further. The corners of buildings are also highly susceptible to seismic damage due to stress concentration (Figure 8f). If irregular structures, such as protruding attics, are present at the corners, the damage in these areas is exacerbated by whip-lash or torsional effects (Figure 8g). In urban areas, due to limited space, it is common for two buildings to be constructed closely together with differing floor heights. This height discrepancy can lead to relative displacement or collisions during an earthquake, further aggravating wall cracking (Figure 8h). Additionally, in rural self-built buildings, the lack of proper regulation often results in weak wall connections or insufficient mortar strength. These deficiencies further undermine the structural integrity, making the walls more prone to localized collapse during seismic events (Figure 8i). In cases of extremely strong seismic forces, this can even lead to the structure's complete collapse (Figure 8j).

Figure 8. Failure modes of load-bearing walls. (**a**) Diagonal cracks at door opening. (**b**) Diagonal cracks at window opening. (**c**) Minor diagonal cracks. (**d**) Severe diagonal cracks. (**e**) Cross cracks; (**f**) Corner cracks. (**g**) Attic cracks. (**h**) Collision cracks. (**i**) Collapse of front longitudinal wall. (**j**) Complete collapse.

3.2.2. Floor or Roof Damage

The floor or roof of masonry structures is primarily constructed using reinforced concrete precast panels and cast-in-place slabs. However, precast panels are more susceptible to damage during earthquakes due to unreliable connections between panels and inherent deficiencies in their overall integrity. Typical seismic damage manifests as longitudinal cracks along the joints between panels (Figure 9a). When the displacement between the panels becomes excessive, the precast panels may even detach from the wall support and fall (Figure 9b). In contrast, cast-in-place slabs, which have superior overall integrity, exhibit significantly better seismic performance. Even if damaged due to the collapse of the supporting walls, they generally only experience localized bending or cracking, rather than completely disintegrating as with precast panels (Figure 9c). This allows them to maintain some degree of structural integrity. In addition to the aforementioned roof types, wooden truss roofs are also relatively common. These roofs typically feature a pitched design, with the trusses directly resting on the walls, and lack effective anchorage connections. This non-rigid connection makes it difficult for the roof and walls to work together cohesively, and the walls' compressive stability is insufficient. The lateral stiffness of these walls is much lower than that of concrete-roofed buildings, resulting in poorer overall structural integrity. In general, the displacement at the top floor during an earthquake is the greatest, and due to the absence of reliable connections in wooden roofs, misalignment and detachment are more likely to occur, potentially leading to catastrophic loss of structural integrity in severe cases (Figure 9d).

Figure 9. Typical seismic damage to floors and roofs. (**a**) Cracking in precast floor slabs. (**b**) Collapse of precast floor slabs. (**c**) Local collapse of cast-in-place floor slabs. (**d**) Collapse of wooden roof truss.

3.2.3. Staircase Damage

The staircase, as a vertical connection passage within a building, is typically not considered a primary load-bearing component during the design phase. However, under seismic forces, the staircase may actually assume a lateral support function. In masonry structures, staircases are generally embedded within the walls, and their failure modes are primarily characterized by transverse or longitudinal force-induced damage. Figure 10 illustrates a range of typical failure modes of staircases. In the structural system, the staircase serves as a continuous opening within the floor slab, which significantly weakens the horizontal stiffness of that region, creating a vulnerable structural layer. The large lateral forces generated by an earthquake, during transmission, are forced to reroute and redistribute due to the presence of the opening, ultimately concentrating around the walls adjacent to the staircase. Furthermore, the embedded stair segments work in tandem with the walls, functioning as a rigid lever to transfer the forces borne by the staircase to the walls, which can cause severe damage due to overloading. In cases of strong seismic action, some staircases may fracture under repeated tensile and compressive forces or, due to platform displacement, may collapse completely.

Figure 10. Typical seismic damage to staircases. (**a**) Transverse cracks on stair flight. (**b**) Longitudinal cracks on stair flight. (**c**) Wall damage in staircase. (**d**) Stair flight collapse.

3.2.4. Foundation and Substructure Damage

The southern Sichuan region is characterized by hilly terrain with significant topographical variations. Before constructing buildings, the site typically requires excavation and leveling. To create a flat foundation, a common practice is to build retaining walls along the edges of the leveled area using stone blocks or bricks. However, due to construction irregularities, two typical issues often arise during this process: first, the site leveling is often insufficient, resulting in inadequate compaction of the foundation soil; second, the stone blocks used for the retaining structures are typically laid without proper bonding or interlocking measures, relying instead on dry-stacking or simple piling methods. Under seismic forces, these rudimentary retaining walls are unable to resist the lateral pressure from the soil behind them due to insufficient friction between the blocks and poor overall integrity. As a result, they partially collapse. Furthermore, because the foundation soil is not sufficiently compacted, uneven settlement is likely to occur under the combined effects of vibration and rainwater infiltration, leading to potential site instability. Currently, such damage is primarily observed at the edges of the courtyards in front of buildings

(Figure 11(a)-1,(a)-2). Although these issues do not pose an immediate threat to the buildings' structural safety, they pose potential risks to future use. Additionally, seismic activity may cause uneven settlement of the foundation, resulting in additional internal forces within the building's upper structure (Figure 11b). When the tensile strength of the masonry walls is insufficient to resist the resulting tensile stresses, diagonal or vertical cracks may form in local sections of the walls (Figure 11(c)-1,(c)-2). This phenomenon highlights that in seismic assessments of hilly areas, the stability of the site and the reliability of the retaining structures should receive equal attention alongside the assessment of the building itself.

Figure 11. Seismic damage to foundations and substructures. (**a**)-1, (**a**)-2 Damage to foundation maintenance structure. (**b**) Foundation damage. (**c**)-1, (**c**)-2 Wall cracks caused by uneven settlement of the foundation.

3.2.5. Non-Structural Components Damage

In masonry structures, the failure of auxiliary components typically manifests as damage to the parapet walls and corridor railings, as shown in Figure 12. These two types of seismic damage are frequently observed in southern Sichuan, and their failure mechanisms and causes are highly similar. On the one hand, a lack of reliable connections between the walls and the main structure compromises structural integrity. On the other hand, the relatively loose construction of the walls themselves results in poor overall stability, making them highly prone to collapse under the horizontal forces induced by an earthquake. Such failures not only severely affect the safety of the structure but also expose critical issues in the design and construction quality control of connection systems. Particularly concerning is the fact that the collapse of these walls often occurs at the building's exit, a critical area for outdoor evacuation and emergency exit, which significantly increases the risk of injury and fatalities.

Figure 12. Accessory components damage. (**a**)-1, (**a**)-2 Parapet wall collapse. (**b**)-1, (**b**)-2 Railing collapse. (**c**) Walkway precast slab falling.

3.3. Simple Building Structures

Simple building structures typically refer to buildings constructed from locally sourced or minimally processed materials, relying on traditional construction methods and experience. These structures generally exhibit weak seismic resistance, as was particularly evident during past seismic events. In southern Sichuan, these building types are primarily brick-wood and earthen structures. These structures are predominantly concentrated in rural areas, with most built in earlier periods and lacking adequate seismic design principles and structural measures. Brick-wood structures are widely constructed and used, with load-bearing brick walls, wood floors and roof systems. These buildings typically have one to two stories. Earthen structures, on the other hand, use rammed earth walls as the primary load-bearing system, with the roof supported by wooden frames. Such buildings are mostly single-story buildings, with relatively few still in existence today. They are commonly found in remote villages or used as auxiliary buildings.

3.3.1. Brick-Wood Structures

Brick-wood structures are highly vulnerable to damage under seismic forces, with the primary failure mechanisms observed in the roof system, load-bearing walls, and overall structural integrity. The roof trusses in these buildings typically consist of a pitched wooden framework, with tiles secured solely by friction and lacking effective fastening mechanisms. Consequently, even in low-intensity seismic zones, roof deformations and inertial forces can readily cause large-scale tile displacement, resulting in both property damage and potential risks to the safety of evacuees (Figure 13a). The load-bearing brick walls serve as the sole components resisting lateral forces; however, many of these buildings were constructed in earlier periods, using bricks with low tensile and shear strength, while low-strength mortars, such as lime-mixed mud, were commonly employed. As a result, the brick exhibits poor tensile and shear performance, with failure modes typically appearing as stepped cracks along mortar joints (Figure 13b). Under seismic loading, diagonal or horizontal shear cracks frequently develop in walls, particularly in areas of stress concentration around door and window openings (Figure 13b,c). Furthermore, a lack of reliable connections between the walls and timber trusses is prevalent. During an earthquake, significant relative displacement between the brick walls and timber trusses can easily cause the trusses to slide off the walls (Figure 13d). In addition, these buildings are generally single-story, with wall thicknesses often limited to 120 mm, resulting in a severe deficiency in lateral stiffness and stability. Under intense vibrations, localized wall collapses (Figure 13e), such as crushing at door and window openings, can trigger a chain reaction of failures, ultimately compromising the overall integrity of the building (Figure 13f). Additionally, some early buildings used hollow-core walls to reduce material costs (Figure 13g), which substantially weakened the effective load-bearing cross-section. The weak mortar bond between the bricks also facilitates relative sliding, significantly reducing the seismic load-bearing capacity and overall integrity of these walls. Therefore, hollow-core walls are highly susceptible to rapid and severe damage or collapse during seismic events.

3.3.2. Rammed Earth Structures

Despite the distinct differences in building materials between rammed earth structures and brick-wood structures, their relatively simple load-bearing systems result in similar overall stress behavior. Consequently, the seismic damage characteristics of both structure types exhibit certain similarities. Rammed earth structures, predominantly constructed in earlier periods, with origins dating back to around the 1960s, exhibit significant material aging. As a result, many pre-existing cracks are evident before seismic events (Figure 14a). Under seismic forces, these existing cracks are prone to further extension and widening, thereby exacerbating the overall structural damage. Similar to brick-wood structures, rammed earth buildings also commonly experience tile displacement in low-intensity seismic zones (Figure 14b). Furthermore, the timber frames in these structures often suffer from material decay, joint loosening, and other related issues due to their age, significantly compromising their load-bearing capacity and seismic resilience. During seismic events, the timber frames are susceptible to localized fractures or even complete collapse (Figure 14c). As the intensity of seismic motion increases, the walls often experience localized or widespread collapse (Figure 14d), leading to the loss of lateral support for the timber frame, ultimately resulting in severe structural damage or complete collapse of the entire structure (Figure 14e,f).

Figure 13. Typical seismic damage to brick-timber structures. (**a**) Slipped roof tiles. (**b**) Stepped cracking. (**c**) Failure of load-bearing wall. (**d**) Collapse of wooden roof. (**e**) Local spalling of wall. (**f**) Complete collapse of building. (**g**) Failure of cavity wall.

Figure 14. Typical seismic damage to earthen structures. (**a**) Widening of pre-existing cracks. (**b**) Slipped roof tiles. (**c**) Failure of wooden roof truss. (**d**) Local collapse of wall. (**e**) Complete collapse. (**f**) Complete collapse.

3.4. Additional Damage

In seismic disasters, isolated non-structural components or auxiliary facilities, in addition to buildings, bear a significantly high risk of collapse. Common examples include display walls, fences, and billboards, as shown in Figure 15. Due to their typically auxiliary functions, these components often receive insufficient attention in structural design, resulting in weak connections to the foundation that lack the necessary anchorage and ties. From a structural mechanics perspective, such walls typically exhibit a tall, narrow, and flat geometry, which results in insufficient out-of-plane stiffness. When the direction of seismic motion is perpendicular to the plane of the wall, the inertial forces can induce substantial oscillatory vibrations of the wall around its base. Should the seismic forces exceed the wall's overturning resistance, there is a high likelihood of out-of-plane instability, ultimately leading to total overturning or fracture collapse.

Figure 15. Typical independent structural seismic damage. (**a**) School display wall collapse. (**b**) Perimeter wall collapse. (**c**) Plaque collapse on a wall.

4. Secondary Disasters and Casualty Analysis

4.1. Seismic Geological Hazards

The landforms in southern Sichuan are characterized by complexity and diversity, primarily comprising basins, hills, mountains, and karst landscapes. This forms a typical geomorphological pattern that transitions from the southern edge of the Sichuan Basin to the Yunnan-Guizhou Plateau. The southern portion of the region features distinctive karst topography, where underground caves and fissures are extensively developed. In some areas, the surface cover is relatively thin, contributing to a fragile overall geological environment [30,31]. In such a geological context, the aftermath of an earthquake is often accompanied by geological disasters such as landslides and collapses, particularly in hilly terrain, where landslides and slope failures along roadways are common. Because the slope's geological structure is loose and the degree of weathering is high, the surface geomaterials are prone to instability under seismic shaking, which can trigger rock dislodgement or even rockfalls. Although large-scale landslides have yet to occur, frequent occurrences of smaller to medium-sized landslides and collapses have had severe impacts on road traffic, leading not only to roadblocks, but also potentially causing further damage to pavements, subgrades, and protective infrastructure (Figure 16(a)-1,(a)-2,(b)-1,(b)-2). Additionally, fallen rock debris entering waterways can obstruct channels, alter hydrological pathways, exacerbate bank erosion, and even compromise the integrity of bridge piers on river-crossing structures, thereby jeopardizing the overall safety of these bridges (Figure 16c). It is particularly noteworthy that some residential areas in this region are situated on mountainous and hilly slopes. Landslides and rockfalls threaten not only roads and bridges, but also residences, causing significant structural damage and potentially resulting in casualties (Figure 16(d)-1,(d)-2). Therefore, during post-earthquake assessments and reconstruction efforts, it is crucial to prioritize the geological stability of hilly and low mountainous areas. There is a need to enhance the identification and monitoring of potential landslide and collapse risk points and implement appropriate engineering protective measures and ecological slope stabilization techniques to improve the region's comprehensive disaster prevention capabilities.

Figure 16. Seismic geohazards. (**a**)-1, (**a**)-2 Landslide. (**b**)-1, (**b**)-2 Road blocked by falling rocks. (**c**) River channel blocked by a landslide mass. (**d**)-1, (**d**)-2 Building destroyed by falling rocks.

4.2. Damage to Lifeline Engineering

Lifeline engineering primarily refers to essential infrastructure systems that support the normal functioning of urban areas, including power and water supply systems and communication networks. Damage to these systems not only disrupts their operations, but may also trigger a cascade of effects, resulting in significant socioeconomic losses [32]. In the context of relatively low-magnitude earthquakes, lifeline structures typically do not experience severe damage from ground shaking alone, except when geological hazards cause large-scale road disruptions. Overall, the extent of seismic damage to lifeline infrastructure remains limited. The observed types of damage can be generally categorized into several key forms. One commonly observed form of damage is the misalignment of bridge expansion joints (Figure 17a). This occurs because expansion joints are designed with a degree of movement capability, and simply supported beam bridges primarily rely on bearings to transfer loads without being strongly restrained in the horizontal direction. As a result, they are prone to swaying during seismic events, which induces displacement responses and leads to misalignment and uneven driving surfaces at the expansion joints. Cracking of highway subgrade surface layers is another typical manifestation of seismic damage (Figure 17b,c), particularly evident on rural roads. This can be attributed to the fact that rural roads often utilize cement concrete only for the surface layer, which functions as a rigid pavement. The underlying subgrade is frequently inadequately compacted, lacking sufficient structural stability. Under repeated seismic loading, the coordination between the subgrade and the surface layer is poor, making the system vulnerable to longitudinal or transverse cracking. Damage to power infrastructure, such as utility poles, has also been observed, typically in the form of tilting or even toppling (Figure 17d). These failures are usually small in scale and are largely attributed to inertial forces generated by seismic ground motion. However, post-earthquake field investigations indicate that the proportion of utility pole failures caused solely by seismic forces is relatively low. Most damage is instead induced by secondary geological hazards such as landslides and rockfalls, which impact and undermine the foundations of pole towers.

Figure 17. Earthquake damage to roads and power lines. (**a**) Bridge displacement. (**b**) Cracks in urban asphalt pavement. (**c**) Cracks in rural concrete pavement. (**d**) Damage to roads and power transmission lines.

4.3. Casualties

In the wake of recent seismic events, casualties are often attributed to a combination of factors. Due to variations in the timing, location, intensity, and social response conditions of different earthquakes, the specific causes of casualties often vary. Table 2 presents a statistical summary of casualty data and causes from three earthquake events. Although the available data samples are limited at this time, some key common features impacting casualties can still be derived from these three representative events. The fatalities are directly related to the destruction of buildings. Specifically, in the Luxian earthquake, two out of the three deceased individuals died as a result of the collapse of the main structure, while one succumbed to injuries inflicted by the falling of a parapet. In the Changning earthquake, all 13 fatalities were attributed to severe damage to the buildings' primary structural components. Similarly, in the Rong County earthquake, two fatalities resulted from the collapse of a balcony. This indicates that even under moderate or weak seismic conditions, the destruction of non-structural or ancillary components, such as parapets, balconies, and exterior wall decorations, may also pose fatal risks. Particularly in rural areas or regions with aging infrastructure, the absence of seismic design measures, coupled with material deterioration or poor construction quality, renders such components more susceptible to localized failure or complete collapse during seismic activity, directly jeopardizing lives. Further analysis of injury cases reveals that damage to ancillary components and improper risk avoidance behaviors are the two primary causes of injuries. In the Luxian earthquake, 14 individuals were injured due to damage from ancillary components, while 41 sustained injuries from inappropriate risk avoidance actions. In the Rongxian earthquake, 10 sustained injuries from ancillary components, and 2 were injured due to improper risk avoidance actions. This reflects two key issues: First, ancillary components of buildings, such as decorative elements, parapets, railings, exterior cladding, and roof tiles, are prone to detachment, fracture, or shattering during earthquakes, creating significant secondary sources of injury (see Figure 12). Second, some individuals lack the scientific knowledge and skills to avoid risks appropriately; for instance, actions such as blindly running during shaking or choosing to shelter near exterior walls, windows, or beneath hanging objects increase the risk of injury. Although a detailed statistical analysis of specific injury causes for the Changning earthquake has not yet been conducted, it is reasonable to infer that similar injury mechanisms were also prevalent in that event.

In summary, the prevention and mitigation of earthquake-related casualties in southern Sichuan should not focus solely on the seismic resistance of primary structural components. Equal attention must be given to the safety performance of non-structural components and ancillary facilities. Although ancillary components are often regarded as secondary elements, their high frequency of damage and broad impact range during seismic events, particularly regarding the significant proportion of injuries they cause, render them a critical weakness within overall seismic resilience. Therefore, during seismic design and retrofitting, technical measures should be implemented to reduce the probability of these components failing during earthquakes, thereby enhancing personnel safety.

Table 2. Statistics on casualties and causes [33,34].

Time	Magnitude	Epicenter	Deaths Number	Cause (Number)	Injuries Number	Cause (Number)
16 September 2021	6.0	Luxian	3	Building collapse (2); Parapet wall collapse (1)	55	Improper evacuation (41); Damage from accessory components (14)
17 June 2019	6.0	Changning	13	Structural damage (10); Precast slab collapse (1); Falling boulders (1); Pre-existing medical condition (1)	226	Improper evacuation and damage from self-built buildings (specific breakdown unavailable)
24/25 February 2019	4.7/4.3/4.9	Rongxian	2	Balcony collapse (2)	12	Improper evacuation (2); Damage from accessory components (10)

5. Retrofitting and Remedial Measures for Existing Buildings

Based on the comprehensive analysis of seismic damage presented above, it can be concluded that the destruction of housing in rural areas is a primary cause of casualties and economic losses. While seismic geological disasters may trigger severe secondary disasters, their broad impact and inherently unpredictable nature make comprehensive prevention and control measures impractical. Therefore, enhancing the seismic performance of residential structures and improving their resilience through effective reinforcement and renovation has become a critical strategy for mitigating losses from seismic disasters. In southern Sichuan, a significant inventory of brick masonry and brick-wood structures exists, with these buildings exhibiting particularly pronounced damage during past seismic events, resulting in notable casualties and economic impact. In contrast, frame structures demonstrate superior seismic resilience, while earthen structures, due to their limited prevalence and tendency to be abandoned, represent a smaller proportion of the overall damage during seismic incidents. Given the structural similarities between brick-wood and brick masonry buildings, many reinforcement measures applicable to one type can be adapted for the other. This paper primarily focuses on brick masonry structures, systematically exploring suitable seismic reinforcement and renovation approaches for such rural residences.

The current overall goal of seismic design standards in China is to ensure that minor earthquakes do not cause damage, moderate earthquakes can be repaired, and major earthquakes do not lead to building collapse. For brick masonry structures, effective seismic design measures are essential in ensuring that significant earthquakes do not cause structural failure. This principle has been sufficiently demonstrated in newly constructed buildings over recent years. However, rural areas face challenges imposed by economic constraints, varying technical capacities, insufficient construction management, and lax government regulation. As a result, many pre-2010 buildings exhibit intrinsic defects, such as inadequate seismic construction and substandard material strength. These conditions make it difficult for such buildings to meet the current seismic retrofitting standards. Therefore, this paper proposes phased reinforcement targets applicable to rural brick masonry buildings. It aims to ensure that when subjected to earthquakes with intensities lower than the basic seismic design level (minor earthquakes), these structures will incur minimal damage and maintain their intended functionality. Furthermore, when exposed to seismic events at the basic design intensity (moderate earthquakes), the buildings' main structural components should not sustain severe damage, and the protective systems should not undergo significant collapse. Moreover, the reinforcement and renovation of rural houses must consider technical feasibility, economic viability, and ease of construction. The goal is to achieve effective seismic resistance within a controllable budget while minimizing disruption to the residents' daily lives and maximizing the potential for broader application. Currently, there are three primary methods for the seismic reinforcement of buildings: the first involves enhancing the seismic performance of individual structural members; the second focuses on improving the overall integrity of existing structures; and the third utilizes special equipment to reduce the seismic forces exerted on the structure. Each of these reinforcement strategies encompasses a variety of specific techniques and methods, thereby providing a rich array of technical options. The following sections will systematically review and consolidate appropriate reinforcement methods for rural brick masonry structures, emphasizing the selection of measures that are straightforward to implement, cost-effective, and easily executable, aiming to provide practical references for earthquake disaster prevention in rural areas.

5.1. Enhancing Structural Integrity

In rural areas, brick masonry structures are generally constructed without ring beams or tie columns. Additionally, the floors are often constructed with precast reinforced concrete slabs that lack effective inter-slab anchorage. As a result, these structures tend to exhibit a relatively loose overall configuration, with poor spatial cooperative performance and significantly inadequate structural integrity. Therefore, enhancing the overall performance of such structures is critical to improving their seismic resistance and ensuring the safety of people and property.

5.1.1. Adding Ring Beams and Tie Columns

Ring beams and tie columns, while not the primary lateral load-resisting components in masonry structures, serve as essential seismic detailing measures. Their function lies in effectively confining the masonry, enhancing structural integrity, and promoting spatial coordination, thereby playing a significant role in improving the overall seismic performance of buildings. For rural brick-concrete buildings in southern Sichuan, typically two to three stories high and located in regions with seismic fortification intensities of VI–VII, according to the Code for Design of Masonry Structures (GB50003 2011) [35] and the Code for Seismic Strengthening Design of Masonry Structures (GB50702 2011) [36], tie columns should be installed at critical locations, including the four corners of exterior walls, intersections of longitudinal and transverse walls, and corners of stairwells. Closed ring beams are also required at the roof level and at each floor level. Based on the current code framework and prevailing practices in seismic retrofitting, this study summarizes several practical, readily implementable structural reinforcement techniques. For installing additional ring beams, a commonly used method is to place continuous longitudinal reinforcement along one or both sides (typically the exterior side) of the wall at the bottom of the floor slabs. These bars are secured with stirrups and anchoring ties, then covered with an outer layer of cement mortar or fine-aggregate concrete to form a reinforced mortar band. Alternatively, an equivalent ring beam system can be constructed by anchoring steel plate strips on both sides of the wall and connecting them with high-strength through-bolts, thereby forming a confinement mechanism with similar restraining effects. The addition of tie columns follows a similar design principle. To accommodate on-site construction conditions, steel plate reinforcement components may be employed as substitutes for conventional reinforced concrete columns. The diameters, spacing, and detailed configurations of the reinforcement bars used in the aforementioned techniques are clearly shown in Figures 18 and 19, providing concrete technical references for engineering implementation.

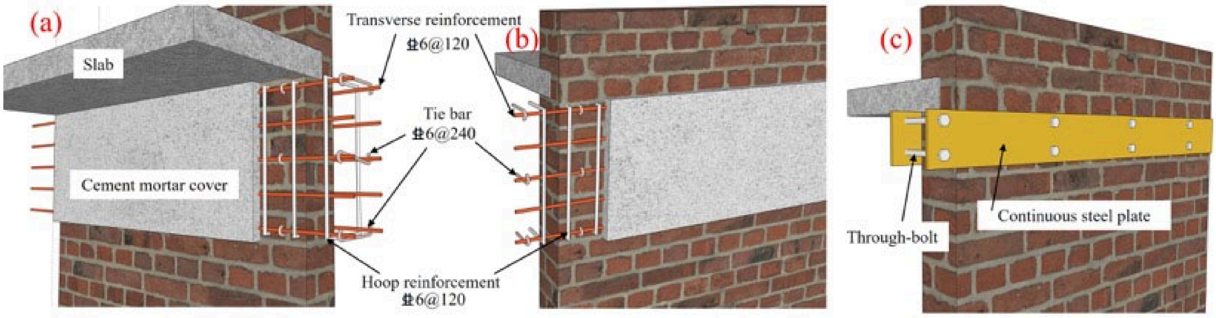

Figure 18. Construction diagram for installing ring beams. (**a**) Retrofitting with reinforced concrete ring beams on both sides. (**b**) Retrofitting with reinforced concrete ring beams on one side. (**c**) Steel plate reinforcement. Note: The brick texture displayed on the walls in all diagrams in Section 7 is solely a visualization effect of the 3D model material, used to differentiate different components, and does not reflect the actual masonry layout or mortar joint structure in the engineering project.

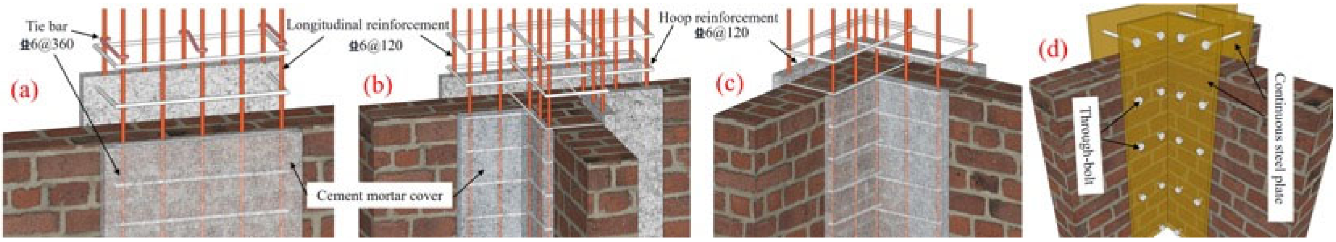

Figure 19. Construction diagram for installing tie columns in various wall configurations. (**a**) Straight wall. (**b**) Intersection of longitudinal and transverse walls. (**c**) Building corner. (**d**) Steel plate reinforcement at the junction of transverse and longitudinal walls.

5.1.2. Strengthening Precast Slab Floors

The primary seismic vulnerability in precast slab floor systems lies in the insufficient effective bearing length at the supports and the lack of reliable anchorage between the slabs and the supporting structures. Under seismic loading, such structural deficiencies can easily lead to slab dislodgement or collapse, potentially triggering a progressive failure cascade, including wall instability and subsequent collapse. Therefore, the reinforcement of precast slab floors must address two key aspects: integrating discrete precast units into a unified structural system to improve in-plane stiffness and overall integrity, and strengthening the connection between slab ends and supporting walls to ensure effective load transfer and more uniform internal force distribution, thereby preventing wall damage due to localized stress concentrations. To achieve both effective reinforcement and construction simplicity, the use of angle steel connectors, based on engineering judgment, represents a practical and efficient method. A schematic representation of the slab reinforcement approach is shown in Figure 20. Specifically, angle steel plates are installed at the vertical support interface between the precast slabs and the wall, serving both to extend the bearing length and to ensure structural continuity. During construction, these steel plates must be securely anchored to both the wall and the slab to establish an effective load-transfer path. On the wall side, high-performance structural adhesives or mechanical anchors may be used to secure the steel plate. On the slab side, however, drilling is not recommended due to internal voids in the precast elements. Instead, non-destructive bonding methods, such as structural adhesive, are preferred to ensure safe and reliable connections. It should be noted that this reinforcement measure is specifically intended for slab end supports. Steel connectors are typically unnecessary along the slab sides running parallel to the wall, to avoid imposing redundant constraints and further simplify construction.

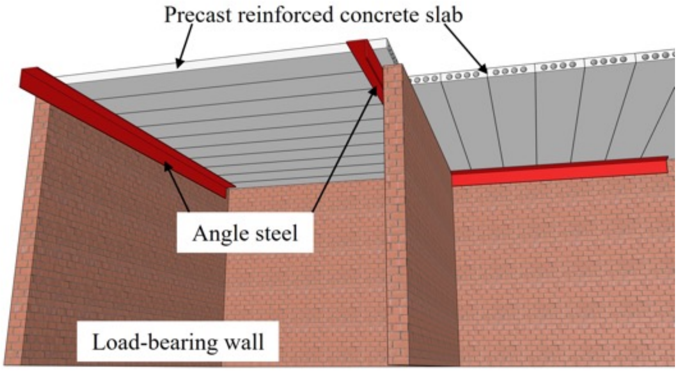

Figure 20. Schematic diagram of precast slab floor reinforcement measures.

5.1.3. Reinforcing Wood Roof Structures

The traditional wooden roof system, characterized by joint connections made through mortise and tenon or simple nails, generally exhibits poor overall integrity. Under seismic forces, components are prone to misalignment, loosening, and even the collapse of the roof trusses. This not only poses a direct safety risk but may also inflict significant damage to the underlying walls. Therefore, the core objective of reinforcing wooden roofs is to strengthen the connections between various roof components and ensure reliable anchoring of the roof structure to the walls. This will transform the roof into a cohesive unit with sufficient rigidity and stability, enabling it to effectively transfer and distribute horizontal forces during an earthquake, thereby preventing localized instability and subsequent progressive failure. Before 2000, the construction method of wooden roofs typically involved placing wooden beams directly on top of the walls, with wooden purlins laid across the beams. Roof tiles were stacked in layers atop the purlins, and stability was mainly maintained through the weight of the tiles and friction between the contact surfaces (Figure 21a). Based on the seismic damage observed in existing wooden roof trusses, the primary modes of failure can be categorized into two types: first, the sliding off of roof tiles; second, the overall detachment of the roof truss from the walls. As these buildings were constructed many years ago, overly complex reinforcement techniques, while effective, present challenges such as high costs and excessive intervention with the original structure. Based on previous applications, at the junction between the wooden beams and the walls, cement mortar or fine aggregate concrete can be poured to form a localized embedded node (Figure 21b). This approach not only enhances the connection performance between the wooden beams and the walls, making it less prone to relative slippage or detachment under horizontal forces, but also, due to the relatively low weight of traditional wooden roof structures, results in smaller inertial forces during an earthquake. The localized strengthening at these junctions significantly enhances the overall resistance to collapse. Upgrading the traditional tile system to a modern glazed tile system is another effective measure to improve roof integrity and prevent tiles from being dislodged during seismic events. Glazed tiles have larger surface areas, providing better friction, and most of them are designed with pre-drilled nail holes or claw teeth on the underside. During construction, the tiles are not simply stacked but fixed directly to the rafters with galvanized copper wire or stainless steel nails, creating a secure bond that makes the tiles an integral part of the roof structure (Figure 21c) rather than merely resting on top. Additionally, the interlocking seams between the tiles are precisely designed, allowing for better engagement. This method has been widely applied in both new construction and renovation projects, offering both technical feasibility and ease of construction. Of course, the aforementioned reinforcement measures assume that the wooden beams possess sufficient load-bearing capacity. If the wooden beams show significant signs of decay, insect damage, or severe degradation of mechanical properties, they must be replaced or locally reinforced before proceeding with further strengthening; otherwise, the reinforcement will not achieve the desired results.

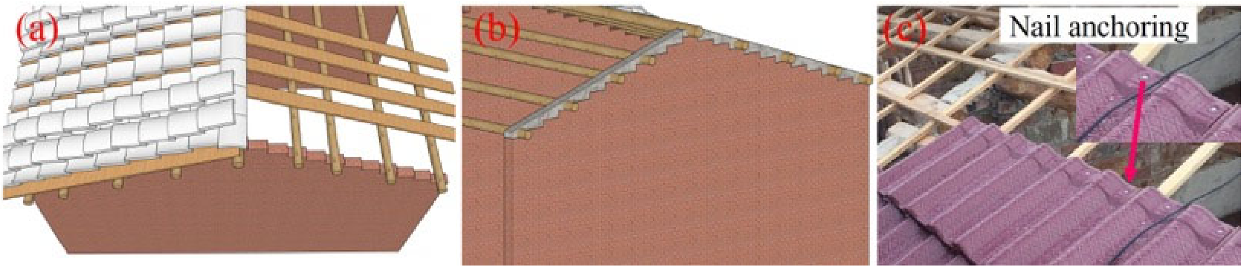

Figure 21. Reinforcement methods for the wooden roof. (**a**) Traditional wooden roof with directly laid rafters. (**b**) Anchorage of wooden frame support ends. (**c**) Replacement of traditional tiles with fixable new-type tiles.

5.1.4. Strengthening Secondary Components

The parapet wall, serving as a low boundary on the roof perimeter of a building, has a relatively high center of gravity and is weakly connected to the underlying structural elements. Under seismic forces, it is highly susceptible to cracking, tilting, or even complete collapse. This not only poses an immediate risk of falling debris causing secondary injuries, but may also compromise the structural integrity of the lower walls or the roof edge due to the impacts of the parapet wall's collapse. Therefore, the primary objective of reinforcing the parapet wall is to enhance its stability and ensure a reliable anchorage with the underlying roof structure or main walls, thereby resisting overturning and sliding during seismic events. According to applicable building codes, parapet walls should incorporate tie columns to improve seismic performance; however, many rural residences in southern Sichuan lack these essential components. As a practical solution informed by an engineering practice perspective, a reinforcement method employing a composite structure of steel plates is proposed to simulate the function of structural columns (Figure 22). The specific procedure is as follows: continuous angle steel should be installed at both ends of the parapet wall and at the junction with the roof. Additionally, continuous steel plates should be arranged along the external face of the load-bearing walls below the parapet wall and anchored to the wall with bolts. Vertical steel columns should connect the continuous sections, with these columns further anchored within the wall using through-bolts. This system not only achieves structural integrity for the parapet wall itself, but also establishes a reliable connection with the roof and wall through the steel connection system. Consequently, this effectively prevents independent tilting or large-scale collapse of the parapet wall during seismic events, significantly enhancing its seismic safety performance.

Railings that exhibit the same failure mechanisms as parapet walls pose significant challenges to overall reinforcement due to their diverse styles, some of which feature openwork designs (Figure 23b,c). These characteristics render them particularly susceptible to overturning, fracturing, and falling during seismic events, which can result in personal injury. Therefore, priority should be given to renovation or replacement strategies. The specific approach involves removing the existing heavy masonry or concrete railings and replacing them with lighter, more ductile stainless steel or lightweight steel railings (Figure 23d). New railing posts should be securely anchored to the underlying walkway beams or walls at both ends and at midpoints, using embedded steel plates or chemical anchor bolts. This modification not only significantly reduces the vertical load imposed by the railings, but also fundamentally eliminates the risk of collapse associated with the original railings.

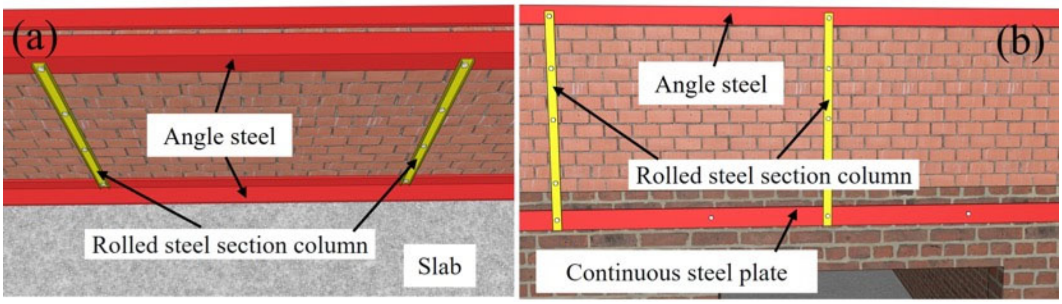

Figure 22. Schematic diagram of parapet reinforcement measures. (**a**) internal view. (**b**) external view.

Figure 23. Different types of railing protective structures. (**a**) Solid brick masonry. (**b**) Hollow brick masonry. (**c**) Hollow precast concrete component. (**d**) Metal railing.

5.2. Improving Wall Load-Bearing Capacity

The walls, as the only structural components in masonry structures that bear both vertical loads and lateral seismic forces, play a crucial role in determining the building's overall safety and durability. However, some existing walls suffer from reduced shear strength, inadequate integrity, and crack propagation due to factors such as degraded mortar bonding, material aging, structural defects, or long-term environmental exposure. These issues severely impair the structure's seismic performance and safety reserves. A more critical concern is that the thickness of existing walls in many buildings is generally quite thin, with most walls being 180 mm thick and some even as thin as 120 mm, which is significantly below the current minimum thickness requirement of 240 mm specified in the building codes. Therefore, conducting systematic inspections and effectively reinforcing the walls have become key measures to enhance the building's seismic capacity and ensure its safety. Given that numerous codes and studies have systematically addressed wall reinforcement techniques, several simple, fast, and cost-effective methods are summarized below. Wall crack repair is a technique that involves pressure grouting or stitching existing cracks to restore the continuity and overall load-bearing capacity of the wall (Figure 24a). Bidirectional reinforced mortar surface treatment is a method in which a steel mesh is applied to the wall surface, followed by spraying high-performance mortar to create a composite load-bearing surface. This approach significantly enhances the wall's shear and bending capacity and has already been implemented in the region (Figure 24b). It is worth noting that traditional reinforced mesh mortar coatings, which require a relatively thick layer to adequately protect the reinforcement, are gradually being replaced by lighter, thinner, high-performance reinforcement methods. With advances in materials technology, the application of carbon fiber-reinforced polymer sheets has become increasingly widespread [37,38]. This method involves adhering carbon fiber fabric or plates to the wall surface (Figure 24c), leveraging their high strength, lightweight, and corrosion-resistant properties to effectively constrain wall deformation, improve shear strength, and significantly enhance the wall's energy dissipation and ductility under cyclic loads. This technique is easy to apply, has minimal impact on the original structure, and is particularly suited for spaces with limited access or for rapid construction. If the wall's quality is not severely compromised, it is also possible to spray fiber-reinforced mortar directly onto the surface without the need for fiber materials (Figure 24d). This low-cost and easy-to-construct method is also very popular in the local area (Figure 24e). Another traditional and effective reinforcement method involves adding buttresses to the external wall (Figure 24f). By placing buttresses at weakened sections or corners and securely anchoring them to the original wall with anchor bars, this method can significantly improve the wall's lateral stiffness and stability, effectively preventing out-of-plane instability and enhancing overall seismic resistance. In addition to traditional brick buttresses, reinforced concrete buttresses can also be used. Vertical reinforcement bars are placed at the anchor bars, and concrete is poured to form an integral system. This not only significantly increases the wall's load-bearing capacity, but also allows the vertical reinforcement bars to contribute to shear resistance, providing a constraining and strengthening effect similar to that of structural columns. The above methods can be reasonably selected and combined based on the current state of the structure, seismic demands, and construction conditions to ensure that the reinforcement measures work synergistically with the existing structure, ultimately achieving a systematic improvement in structural safety and seismic performance. In addition to the aforementioned methods, some research teams abroad have also achieved notable results. For example, Formisano and Longobardi [39] developed an innovative solution that combines metal exoskeletons with insulation panels to enhance seismic resistance while reducing thermal dispersion. This method has been widely adopted in Europe.

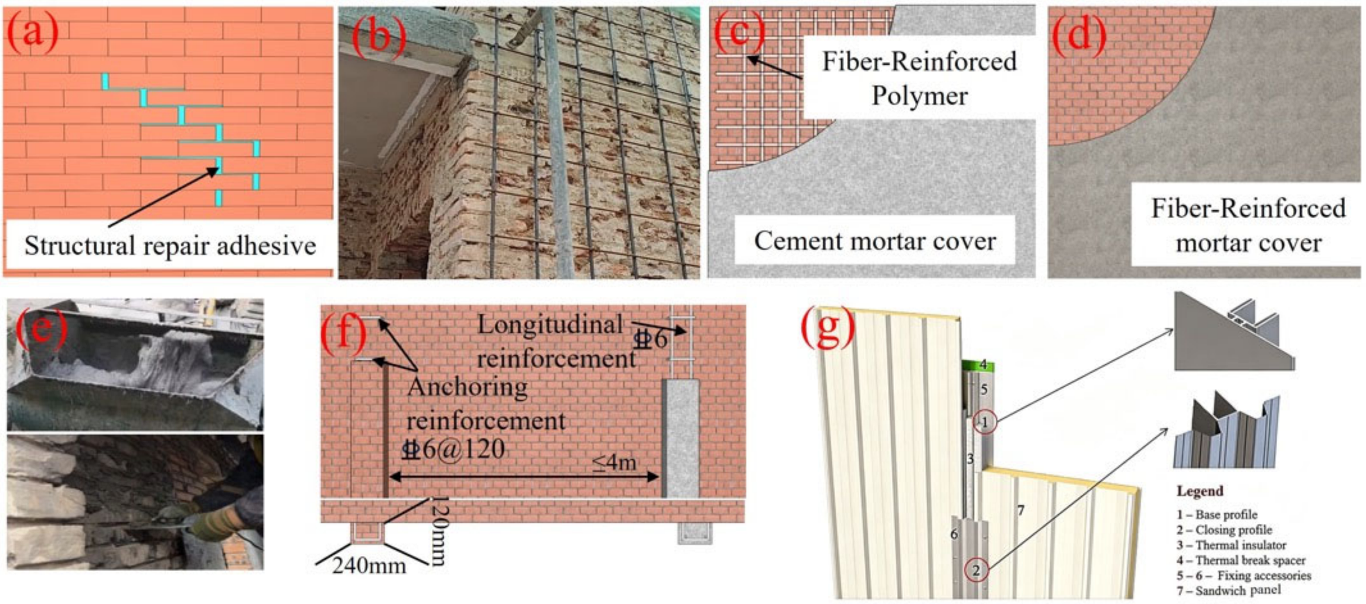

Figure 24. Wall load-bearing capacity enhancement measures. (**a**) Wall crack repair; (**b**) externally bonded steel mesh reinforcement; (**c**) externally bonded fiber-reinforced polymer reinforcement; (**d**) enhanced mortar rendering; (**e**) addition of buttresses; (**f**) addition of buttresses; (**g**) MIL 15.s Eco-Seismic Insulation System [39].

5.3. Optimizing Vertical Load-Resisting Systems

When buildings exhibit irregular geometric shapes or an uneven distribution of stiffness and mass centers, significant eccentric torsional effects can occur under seismic actions. This exacerbates localized stress concentrations within walls, potentially leading to severe structural damage. Such issues are particularly prevalent in brick-concrete structures in southern Sichuan, where cantilevered structures are commonly found on the second floor and above. This design introduces abrupt changes in vertical stiffness and discontinuities in the center of mass, resulting in the connections between the first and second-floor walls becoming weak points in terms of seismic resistance. These areas are prone to cracking or even localized collapse during an earthquake. To address these safety concerns, some residents have implemented various rudimentary reinforcement measures. These measures primarily include constructing additional brick walls on both sides of the cantilevered sections to enhance lateral support or installing brick columns at the junctions of cantilever beams to provide localized support (Figure 25a,b). However, only a small number of buildings incorporate diagonal bracing under each cantilever beam at the time of construction, with the opposite ends anchored to the foundation (Figure 25c). This configuration enables a more direct transfer of vertical loads to the foundation, effectively alleviating the forces and eccentricity associated with the cantilevered sections. Nevertheless, these diagonal braces hinder movement in certain areas, often relegating lower spaces to storage.

Figure 25. Current self-designed reinforcement measures by residents. (**a**) Later-added brick wall. (**b**) Later-added brick column. (**c**) Additional reinforced concrete diagonal bracing.

Based on engineering experience, this paper proposes a composite reinforcement strategy that combines active load reduction with anchorage enhancement (Figure 26a). First, diagonal steel braces are installed beneath the cantilevered section. This configuration not only significantly shortens the effective span of the cantilever beam, but more importantly, diverts a portion of the cantilever load directly to the underlying main structure. Second, high-strength anchorages are installed at the fixed end of the cantilever beam to provide a rigid connection to the rear wall, thereby resisting the uplift force induced by the cantilever moment and ensuring joint integrity. This method effectively suppresses excessive deflection and warping of the cantilever beam under vertical loads and seismic excitation, thereby enhancing its load-bearing capacity, stiffness, and overall seismic performance. In addition to vertical irregularities caused by cantilevered components, another common form of structural irregularity is observed when the ground floor of a building is recessed by approximately one bay in depth. In such configurations, the beam ends of the recessed walls are supported by brick columns that lack internal reinforcement (Figure 26b). This structure differs from the condition illustrated in Figure 25b in that the brick columns here serve as non-structural supplementary members. Even in the absence of these columns, the structure remains stable under gravity loads. However, in the latter case, where the cantilever span extends approximately three meters, the brick columns are essential for carrying the primary vertical loads. Under normal service conditions, these brick columns are subjected mainly to axial compression and generally maintain structural safety. Nevertheless, during seismic events, significant differential shear deformation may occur between the walls and the brick columns, potentially leading to brittle failure due to the inadequate shear capacity of the unreinforced masonry. To mitigate this risk, it is recommended that steel angle bars be installed at the four corners of each brick column and connected into an integrated system with batten plates. This combined wrapping reinforcement method can effectively improve the stiffness, ductility, and deformation compatibility of the columns, thereby enhancing their seismic performance.

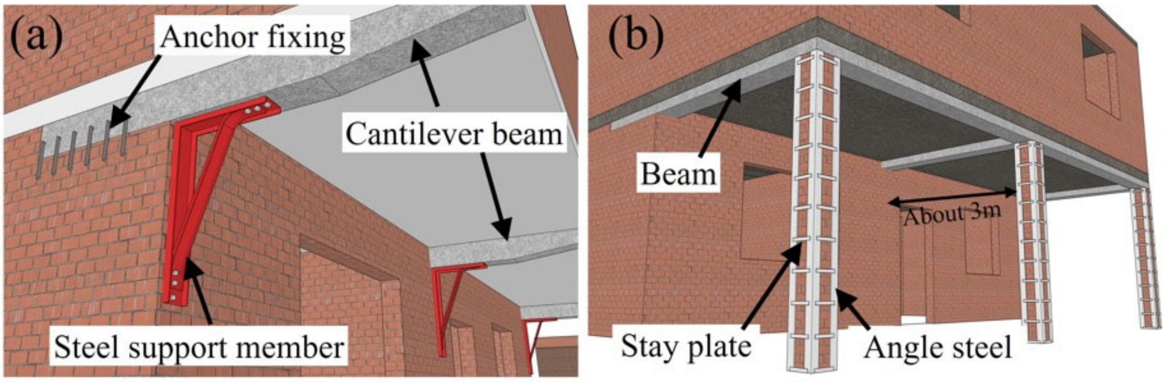

Figure 26. Reinforcement of vertically irregular masonry structures. (**a**) Enhancing the support capacity of cantilever structures using triangular steel braces. (**b**) Enhancing the load-bearing capacity of brick columns using encased steel sections.

6. Practical Implications for Disaster Risk Reduction

Based on a systematic analysis of the complete disaster chain, covering seismic frequency, ground motion intensity, structural damage, secondary geological hazards, lifeline performance, and casualty outcomes, this research provides a holistic view of earthquake disaster features in southern Sichuan. The analytical framework established provides a multidimensional and comprehensive scientific basis for regional disaster prevention and mitigation. Specifically, the research findings can be translated into practical applications and decision support through the following pathways. In disaster prevention planning, understanding the distribution and building characteristics of various structural types in the region, along with their typical damage patterns, enables an initial estimate of the potential damage levels. This enables local authorities to delineate high-risk zones and establish priority rankings for seismic retrofitting based on structural typology and spatial distribution. Moreover, the retrofitting measures proposed in this study can be directly applied to these priority areas. These analyses provide a clear foundation for the rational allocation of disaster prevention resources in the medium- and long-term, ensuring that limited resources are channeled to the buildings most in need of strengthening. For emergency response, the cascading relationships between ground motion, building damage, lifeline disruptions, and casualties are elucidated. These relationships provide scientific support for local governments to optimize post-earthquake rapid assessment procedures and also facilitate the pre-deployment of emergency response teams and supplies. Together, these efforts contribute to the formulation of more efficient emergency plans. For post-disaster recovery and reconstruction, this study establishes a correlation between typical building damage patterns and reinforcement measures. This provides a technical reference for safety assessments, repairability evaluations, and reconstruction planning. As a result, the economic efficiency and timeliness of recovery efforts can be improved. Finally, it is worth noting that cases in which the vertical PGA exceeds two-thirds of the horizontal PGA are not uncommon in the study region. However, the current seismic design code does not adequately address such conditions, and its relevant provisions appear non-conservative. Therefore, it is recommended that the code be revised to adopt a higher design value for vertical seismic action to more accurately reflect the actual characteristics of ground motion, thereby enhancing the reliability and safety of seismic structural design.

In summary, this paper systematically characterizes the earthquake disaster chain in southern Sichuan. It also translates scientific findings into practical tools and decision support to enhance regional seismic resilience and disaster prevention capacity.

7. Conclusions

This study focuses on the southern Sichuan region and provides a systematic review of the spatial and temporal distribution patterns of seismicity. Drawing on historical earthquake data and on-site investigations, it details the spatial distribution of macroseismic intensities. Strong-motion records are further analyzed across multiple dimensions, with emphasis on spectral characteristics, amplitude variations, and duration. A key aspect of the study is the classification of typical failure modes and damage evolution mechanisms for various structural types under seismic loading. The research also extends to the distribution patterns of secondary geological disasters, the seismic damage characteristics and failure mechanisms of lifeline engineering systems, and the spatial distribution of casualties, along with their primary contributing factors. Based on these findings, the study identifies the seismic vulnerabilities and earthquake risks of rural masonry buildings prevalent in southern Sichuan, particularly issues related to construction practices, material quality, and connection details. Considering regional economic constraints and construction feasibility, it proposes several cost-effective and easy-to-implement seismic retrofitting techniques. These techniques aim to enhance overall structural integrity, improve the shear and overturning resistance of walls, and optimize vertical and horizontal load-bearing systems. Corresponding design guidelines and construction recommendations are provided. Furthermore, the effective translation of the aforementioned findings into practical applications and decision-making processes is detailed. The main conclusions are as follows:

(1) The seismicity in the southern Sichuan region shows a significantly increasing trend, with frequent moderate-to-strong earthquake events and relatively shallow focal depths. This trend not only implies an increase in regional ground motion intensity and thus greater potential destructiveness, but also that the cumulative fatigue damage caused by frequent low-intensity vibrations during seismic activity should not be overlooked.

(2) Seismic events have generally exhibited high intensity, with local site intensities significantly exceeding the current seismic design standards. The recorded ground motions are characterized by short durations, abundant high-frequency components, and pronounced vertical acceleration. Moreover, the ratio of vertical to horizontal accelerations often exceeds the values recommended by existing codes. Therefore, a reassessment of regional seismic design parameters is warranted, and the effects of vertical ground motion should be fully considered in seismic design.

(3) The large-scale presence of masonry structures and masonry-wood structures reveals a pronounced mismatch between the seismic capacity of buildings and the corresponding design requirements. Many old residential buildings and self-built masonry houses in rural towns exhibit low material strength and insufficient structural measures, such as the absence of ring beams and structural columns. These deficiencies result in severe damage during earthquakes, making such buildings a primary source of casualties and economic losses. Meanwhile, although framed structures generally demonstrate relatively good seismic performance, some school buildings with frames suffer from improper arrangement of frame columns and infill walls. This irregularity leads to stress concentrations and an uneven distribution of stiffness, significantly

increasing column-end shear forces and raising the risk of brittle shear failure, thereby posing a substantial seismic safety concern.

(4) Earthquake-induced geological hazards and damage to lifeline infrastructures have generally been minor. However, the mountainous terrain exacerbates the frequency and severity of secondary disasters, such as landslides and collapses, creating considerable obstacles to restoring transportation and communication systems.

(5) Casualties are not only associated with the collapse of primary structural components; damage to non-structural elements, including partition walls, decorative components, and utility pipelines, can also result in serious injuries. Consequently, seismic design must ensure the overall safety of both structural and non-structural systems.

(6) The proposed seismic retrofitting system for masonry buildings, centered on "overall strengthening, wall reinforcement, and system optimization", combines economic feasibility, practicality, and operability. This approach can significantly enhance the seismic performance of such buildings, effectively mitigate earthquake risks, and be widely applied in similar regions.

(7) Based on a comprehensive analysis of the complete disaster chain, the results are directly applicable to routine prevention planning, emergency response, recovery and reconstruction, code revision, and other relevant areas in southern Sichuan, thereby holistically improving the region's earthquake resilience and disaster mitigation performance.

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References

1. *GB 18306*; Seismic Ground Motion Parameters Zonation Map of China. National Standards of People's Republic of China: Beijing, China, 2015. (In Chinese)
2. Lei, X.L.; Su, J.R.; Wang, Z.W. Growing seismicity in the Sichuan Basin and its association with industrial activities. *Sci. China Earth Sci.* **2020**, *63*, 1633–1660. [CrossRef] [PubMed]
3. Khanmohammadi, M.; Eshraghi, M.; Sayadi, S.; Mashhadinezhad, M.G. Post-earthquake seismic assessment of residential buildings following Sarpol-e Zahab (Iran) earthquake (Mw7.3) part 1: Damage types and damage states. *Soil Dyn. Earthq. Eng.* **2023**, *173*, 108121. [CrossRef]
4. Lagomarsino, S. Damage assessment of churches after L'Aquila earthquake (2009). *Bull. Earthq. Eng.* **2012**, *10*, 73–92. [CrossRef]
5. Longobardi, G.; Milani, G.; Formisano, A. Seismic Vulnerability Assessment of Churches Affected by the 2012 Emilia-Romagna Earthquake: Comparison among Different Approaches. In Proceedings of the 2024 IEEE International Workshop on Metrology for Living Environment (MetroLivEnv), Chania, Greece, 12–14 June 2024; pp. 327–331. [CrossRef]
6. Liu, C.Q.; Fang, D.J.; Zhao, L.J. Reflection on earthquake damage of buildings in 2015 Nepal earthquake and seismic measures for post-earthquake reconstruction. *Structures* **2021**, *30*, 647–658. [CrossRef]
7. Caglar, N.; Vural, I.; Kirtel, O.; Saribiyik, A.; Sumer, Y. Structural damages observed in buildings after the January 24, 2020 Elazığ-Sivrice earthquake in Türkiye. *Case Stud. Constr. Mater.* **2023**, *18*, e01886. [CrossRef]
8. Dedeoğlu, İ.Ö.; Yetkin, M.; Calayır, Y. Seismic performance of masonry structures in the rural area during the November 23, 2022, Düzce-Gölyaka earthquake. *J. Build. Eng.* **2024**, *96*, 110373. [CrossRef]
9. Damcı, E.; Temür, R.; Kanbir, Z.; Şekerci, Ç.; Köroğlu, E.Ö. Comprehensive investigation of damage due to 2023 Kahramanmaraş Earthquakes in Türkiye: Causes, consequences, and mitigation. *J. Build. Eng.* **2025**, *99*, 111420. [CrossRef]

10. Avğın, S.; Köse, M.M.; Özbek, A. Damage assessment of structural and geotechnical damages in Kahramanmaraş during the February 6, 2023 earthquakes. *Eng. Sci. Technol. Int. J.* **2024**, *57*, 101811. [CrossRef]
11. Kırtel, O.; Aydın, F.; Boru, E. Seismic damage assessment of under-construction industrial buildings: Insights from the february 2023 Türkiye-Syria earthquakes. *Case Stud. Constr. Mater.* **2024**, *21*, e03507. [CrossRef]
12. Toprak, S.; Zulfikar, A.C.; Mutlu, A.; Tugsal, U.M.; Nacaroglu, E.; Karabulut, S.; Ceylan, M.; Ozdemir, K.; Parlak, S.; Dal, O.; et al. The aftermath of 2023 Kahramanmaras earthquakes: Evaluation of strong motion data, geotechnical, building, and infrastructure issues. *Nat. Hazards* **2025**, *121*, 2155–2192. [CrossRef]
13. Akinci, A.; Dindar, A.A.; Bal, I.E.; Ertuncay, D.; Smyrou, E.; Cheloni, D. Characteristics of strong ground motions and structural damage patterns from the February 6th, 2023 Kahramanmaraş earthquakes, Türkiye. *Nat. Hazards* **2025**, *121*, 1209–1239. [CrossRef]
14. Bai, W.; Dai, J.W.; Liu, R.H.; Shao, Z.P.; Yang, Y.Q.; Jiang, T.; Zhou, B.F. Site investigation on seismic performance of 7 isolated buildings during the 2022 Luding Ms6.8 earthquake. *J. Build. Eng.* **2024**, *89*, 109224. [CrossRef]
15. Xiao, B.F.; Miao, L.; Luo, A.Y.; Qi, Y.P.; Liang, H.L.; Gesang, Z.X.; Liu, Y. Analysis of the Damage Characteristics and Cause of the 2017 Junlian MS4.9 Earthquake in Sichuan Province. *China Earthq. Eng. J.* **2017**, *39*, 202–208. (In Chinese) [CrossRef]
16. Yang, Y.Q.; Bai, W.; Dai, J.W.; Chen, X.Z. Investigation and analysis of building damage caused by the Ms6.0 Changning earthquake in Sichuan Province. *Build. Struct.* **2023**, *53*, 738–743. (In Chinese) [CrossRef]
17. Pan, Y.; Chen, J.; Bao, Y.L.; Peng, X.; Lin, X.C. Seismic damage investigation and analysis of rural buildings in Ms6.0 Changning earthquake. *J. Build. Struct.* **2020**, *41*, 297–306. (In Chinese) [CrossRef]
18. Pan, Y.; Yi, D.H.; You, W.L.; Fan, Y.Q.; Lin, X.C. Seismic damage investigation and analysis of rural buildings in Ms6.0 Luxian earthquake. *China Civ. Eng. J.* **2023**, *56*, 47–59. (In Chinese) [CrossRef]
19. Yi, G.X.; Long, F.; Liang, M.J.; Zhao, M.; Wang, S.W.; Gong, Y.; Qiao, H.Z.; Su, J.R. Focal mechanism solutions and seismogenic structure of the 17 June 2019 Ms6.0 Sichuan Changning earthquake sequence. *Chin. J. Geophys.* **2019**, *62*, 3432–3447. (In Chinese) [CrossRef]
20. Yi, G.X.; Zhao, M.; Long, F.; Liang, M.J.; Wang, M.M.; Zhou, R.J.; Wang, S.W. Characteristics of the seismic sequence and seismogenic environment of the Ms6.0 Sichuan Luxian earthquake on September 16, 2021. *Chin. J. Geophys.* **2021**, *64*, 4449–4461. (In Chinese) [CrossRef]
21. Shi, S.Z.; Shen, J.W. Discussion on the problem of frequent earthquakes in seismic design. *Acta Seismol. Sin.* **2012**, *34*, 105–110. (In Chinese)
22. *GB/T 17742*; The Chinese Seismic Intensity Scale. National Standards of People's Republic of China: Beijing, China, 2008. (In Chinese)
23. *GB 50011*; Code for Seismic Design of Buildings. National Standards of People's Republic of China: Beijing, China, 2016. (In Chinese)
24. Morales, C.A. Seismic Structural Resonance Observation Based on Recent Estimation of Earthquake Predominant Frequency. *Buildings* **2025**, *15*, 4485. [CrossRef]
25. Sivori, D.; Cattari, S.; Lepidi, M. A methodological framework to relate the earthquake-induced frequency reduction to structural damage in masonry buildings. *Bull. Earthq. Eng.* **2022**, *20*, 4603–4638. [CrossRef]
26. Pan, Y.; Zhang, L.L.; Lin, X.C.; Zhang, B. Simulation and Mechanism Analysis of Seismic Damage to Urban Buildings Groups during the Ms 6.0 Luxian Earthquake. *J. Disaster Prev. Mitig. Eng.* **2024**, *44*, 977–986. (In Chinese) [CrossRef]
27. Dong, X.Y.; Lata, A.; Guo, X.; Luo, R.F.; Yan, C. Study on seismic performance of semi-enclosed buildings based on shaking table test. *Structures* **2025**, *81*, 110315. [CrossRef]
28. Luo, R.F.; Guo, X.; Wang, B.; Dong, X.Y.; Zhang, Q.Z.; Ouyang, Z.Y. The impact of infill wall distribution on the mechanical behavior and failure patterns of multi-story RC frame structures: An acceleration–strain coupled testing approach. *Structures* **2024**, *59*, 105737. [CrossRef]
29. Zhang, J.; Lata, A.; Guo, X.; Liu, X.C.; Wang, Y.B.; Liu, Y.L. A simplified seismic design optimization approach for RC school buildings with cantilevered outdoor corridors considering local infill-frame interactions. *J. Build. Eng.* **2025**, *110*, 113085. [CrossRef]
30. Liu, W.; Yu, T.B.; Wang, M.; Li, D.; Huang, X.C.; Dong, J.H. Analysis on the relationship between geological hazard and lithology, geological structure in Yibin City of Sichuan Province. *Chin. J. Geol. Hazard Control* **2023**, *34*, 118–126. (In Chinese) [CrossRef]
31. Zhu, D.C.; Zou, H.Y.; Yang, M.L.; Li, T.; Li, T.; Li, H.P.; Xu, L.; Wen, L.; Zhou, G. The Middle Permian Maokou reservoir (southern Sichuan Basin, China): Controls on karst development and distribution. *J. Pet. Sci. Eng.* **2021**, *204*, 108686. [CrossRef]
32. Wang, K.G.; Zheng, S.S.; Cai, G.W.; Tian, Q. Resilience of lifeline systems under seismic events: A rapid assessment based on machine learning surrogate models. *Structures* **2025**, *77*, 109033. [CrossRef]
33. Dai, Y.L.; Liu, Y.; Liang, Y.L.; Xiao, B.F.; Yang, L.Y. Comparative Analysis of Casualties between Lushan M6.1 Earthquake and Luxian M6.0 Earthquake. *Technol. Earthq. Disaster Prev.* **2022**, *17*, 674–681. (In Chinese) [CrossRef]

34. Yan, J.X.; Ye, Z.H.; Zheng, Y.; Shi, B.X. Investigation of Building Damage Characteristics and Human Casualties in Relation to the Ms4.7, Ms4.3, and Ms4.9 Earthquakes Occurring in Rong County. Sichuan Province. *China Earthq. Eng. J.* **2020**, *42*, 1019–1023. (In Chinese)
35. *GB 50003*; Code for Design of Masonry Structures. National Standards of People's Republic of China: Beijing, China, 2011. (In Chinese)
36. *GB 50702*; Code for Seismic Strengthening Design of Masonry Structures. National Standards of People's Republic of China: Beijing, China, 2011. (In Chinese)
37. Cosgun, T.; Uzdil, O.; Sayin, B.; Zengin, K.K. Seismic vulnerability assessment of a masonry structure and an FRP-strengthening proposal. *Case Stud. Constr. Mater.* **2022**, *17*, e01680. [CrossRef]
38. Gkournelos, P.D.; Triantafillou, T.C.; Bournas, D.A. Seismic upgrading of existing masonry structures: A state-of-the-art review. *Soil Dyn. Earthq. Eng.* **2022**, *161*, 107428. [CrossRef]
39. Formisano, A.; Longobardi, G. Seismic fragility and energy efficiency upgrading of masonry compounds using lightweight aluminium alloy exoskeletons: A case study in South Italy. *Bull. Earthq. Eng.* **2026**, *24*, 2735–2753. [CrossRef]