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Characteristics of Damage to Rural Houses in the High-Intensity Area of the Jishishan *Mw* 6.2 Earthquake

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Abstract: On 18 December 2023, a 6.2-magnitude earthquake struck Jishishan, affecting multiple counties and cities in Gansu and Qinghai Provinces. The seismic intensity of the meizoseismal area was VIII, resulting in extensive structural damage and building collapses. A damage assessment was conducted of the epicenter and surrounding high-intensity zones. To understand the typical structures and characteristics of the buildings that were damaged in these high-intensity zones, this study summarizes the characteristics of the damage to typical rural houses, compares the damage of the rural houses across different sites, and analyzes the causes behind these variations. The findings of the study indicate the following: (1) Timber and some brick–timber structures, due to their age, insufficient material strength, and lack of adequate connections between parts of the building, primarily experienced severe damage or total collapse, characterized by through-wall cracks, partial collapses, or complete collapses. (2) Brick–concrete structures predominantly suffered moderate to severe damage due to factors such as improper layout, uneven façades, and inadequate or incomplete seismic measures. The observed damage included significant wall cracks and extensive damage to two-story buildings. (3) Frame structures, mainly used for public facilities like schools, hospitals, and health centers, exhibited strong integrity and excellent seismic performance, resulting in minimal to no damage, with damage largely confined to non-load-bearing components. (4) The amplification effects of seismic waves in thick loess basin areas, slope sites, and the hanging wall effect of faults exacerbated structural damage to rural houses located in certain villages within the high-intensity areas. The results of this study can serve as a reference for post-disaster reconstruction and seismic retrofitting of buildings and contribute positively to enhancing the disaster resilience of rural housing.

Keywords: Jishishan earthquake; high-intensity area; rural house structure; earthquake damage characteristics; site effects

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1. Introduction

Earthquakes are some of the most serious natural disasters. Many countries are seriously threatened by earthquakes. Buildings are the most direct disaster-bearing bodies of earthquakes. Therefore, studying the damage law of buildings and proposing targeted seismic measures are significant for improving the seismic capacity of buildings and reducing earthquake losses. In the past 20 years, the frequency of destructive earthquakes has been high, and experts and scholars have conducted more research on building damage. Ozcan et al. analyzed the damage data of 331,061 buildings in the area affected by the February 2023 Amanos earthquake in Turkey by using binary logistic regression analysis and revealed the quantitative relationship between altitude and building damage [1]. Amry et al. conducted a post-earthquake assessment of buildings in the West Sulawesi Island earthquake in Indonesia and put forward suggestions for subsequent reconstruction [2]. Ramírez et al. assessed the seismic damage of more than 160 adobe buildings in four cities

of Morelos state in the September 2017 earthquake in Mexico and assessed the vulnerability of buildings to earthquakes [3]. Sabeur et al. evaluated 199 masonry buildings with different uses in Mostaganem city in Algeria by the RISK-UE method and determined the seismic vulnerability index [4]. Ornthammarath et al. conducted a post-disaster survey of buildings in the 6.1-magnitude earthquake in the Mekong–Laos region of Thailand. Based on the different degrees of structural and non-structural post-earthquake damage and the data collected from the local official database, using these loss observations, the vulnerability function of the building was derived and compared with the vulnerability function developed for damaged residential buildings in the same area. It was concluded that the failure of non-structural components may lead to serious injuries and casualties [5].

China is one of the countries with the most serious earthquake disasters in the world. A total of 80% of the destructive earthquakes occur in rural areas in China, causing far more damage to houses and economic losses than in cities. Therefore, it is of great significance to carry out a detailed investigation of the damage to rural residential buildings after an earthquake, summarize the characteristics of the damage to different residential structures, and analyze the seismically weak links in residential structures. It can help with not only quickly obtaining the seismic damage information from residential buildings and carrying out emergency rescue work in a timely and targeted manner but a.lso strengthening and repairing the weak seismic links of residential buildings or using seismic structural measures for new buildings after the disaster, which is significant for improving the seismic capacity of residential buildings and reducing earthquake losses.

Acito M. analyzed different damage scenarios in the historic centers and the different degrees of damage of the buildings that were caused by the seismic events of May 2012, in Emilia and of August–October 2016 in Central Italy [6]. Structural damage to the masonry of buildings during earthquakes of magnitude 7.7 and 7.6 in rural areas of Kahramanmaras province were examined in detail [7]. After the 4 April 2019 earthquake in Turkey, the damage patterns of masonry buildings and adobe dwellings in the villages of Sivrice were assessed in detail [8]. Based on the investigation of the earthquake damage of different types of houses in the Minle-Shandan earthquakes (Mw = 5.8, Mw = 5.2) in 2003, the characteristics of earthquake damage and the distribution characteristics of the macro-seismic intensity of different kinds of dwellings were used to reveal the causes of earthquake damage to the houses [9,10]. The damage characteristics of the brick–concrete structures in Qingchuan County in Sichuan Province and timber frame houses in Longnan City of Gansu Province triggered by the Wenchuan earthquake (Mw = 7.9) were investigated, and the causes of the rural house damage were analyzed [11,12]. Shao et al. assessed the building damage of the Yushu earthquake (Mw = 6.8) in 2010, analyzed the characteristics of building damage, and put forward countermeasures for earthquake prevention and disaster reduction [13]. Qu et al. summarized and analyzed the seismic damage characteristics of unconstrained masonry structures and wooden frame residential buildings in western Sichuan based on investigating building damage in different-intensity areas of the Lushan earthquake (Mw = 6.7) in 2013 [14]. Wang et al. systematically studied the seismic damage characteristics and failure mechanisms of buildings in different-intensity areas of the Minxian–Zhangxian earthquake (Mw = 5.9) in 2013 and summarized the seismic damage characteristics such as fault effects, mountain amplification, and slope effects [15]. Sun summarized the seismic damage characteristics of non-structural components by investigating and describing the seismic damage of different typical structural and non-structural components in the Jiuzhaigou earthquake (Mw = 6.5) in 2017 [16]. Xiong et al. summarized the failure characteristics of brick–concrete buildings in the Jiuzhaigou earthquake (Mw = 6.5) in 2017, and the influence of seismic structural measures on the seismic performance of brick–concrete buildings was analyzed by comparing the time-history analysis results with the seismic damage [17]. Sun et al. summarized the seismic damage characteristics of wooden frame buildings in the Jiuzhaigou Mw 6.5 earthquake in 2017, compared the seismic damage of brick–concrete structures, and summarized the reasons for the differences in the seismic damage to the wooden frame rural buildings [18]. Wang et al.

summarized the general characteristics of the seismic damage to residential buildings in the low-intensity area of Wenxian County, Gansu Province, in the 2017 Jiuzhaigou *Mw* 6.5 earthquake, analyzed the seismic damage characteristics of the intensity anomalies in low-intensity areas, and discussed the causes of these intensity anomalies [19]. Du et al. analyzed the structural characteristics, seismic damage characteristics, and seismic damage distribution of Tibetan wooden frames in the Xiahe *Mw* 5.7 magnitude earthquake in 2019 and deeply analyzed the seismic measures and failure mechanisms of Tibetan wooden frame houses [20]. Luo et al. analyzed the seismic damage characteristics and failure causes of masonry structures and frame structures in the Luding earthquake (*Mw* = 6.6) in 2022 [21]. Wang et al. analyzed the seismic damage characteristics of different buildings (structures) and lifeline projects in the areas with seismic intensity between VI and VIII of the Jishishan earthquake (*Mw* = 6.2) in 2023 [22]. From the aspects of seismic design and construction management, site amplification effects, and the influence of secondary disasters on the seismic performance of building structures, the seismic damage caused by the earthquake was put forward. Wang et al. [23], Gao et al. [24], and Guo et al. [25,26] have analyzed the disaster characteristics of the Jishishan *Mw* 6.2 earthquake in 2023 and believed that the amplification of seismic waves was the main cause of the collapse of a large number of houses.

On 18 December 2023, a *Mw* 6.2-magnitude earthquake occurred in Jishishan County, Linxia City, Gansu Province (after this, called Jishishan County) (35.7° N, 102.79° E). The focal depth was 10 km. The instrument epicenter was located in Liugou Town, Jishishan County, however, the macroscopic epicenter was Dahejia Town, Jishishan County. The earthquake caused a large amount of house damage and property losses; the direct economic losses amounted to CNY 14.612 billion. Field investigation is the primary task of earthquake engineering and disaster prevention and mitigation research. Summarizing the seismic defects of building structures due to earthquakes, analyzing the potential seismic risks of residential buildings, and drawing lessons from house damage can provide a reference for post-disaster reconstruction and post-earthquake building reinforcement and transformation, to improve the disaster prevention ability of residential buildings. Based on the site investigation, this paper summarizes the seismic damage characteristics of typical rural houses in the high-intensity area of the Jishishan *Mw* 6.2 earthquake, analyzes the failure law and seismic damage mechanism of each structural type, and discusses the influence of the hanging wall effect, site type, and seismic wave attributes on rural seismic damage. This study focuses on the high-intensity area of the Jishishan earthquake, studies the seismic damage characteristics of typical residential structures in rural areas, compares the seismic damage performance of residential buildings without seismic structural measures and buildings built according to local seismic fortification requirements, and preliminarily analyzes the causes of serious seismic damage and seismic damage differences in high-intensity areas. The conclusions obtained will be helpful for improving the seismic capacity of rural residential buildings and popularizing and applying seismic fortification codes.

2. Background

Jishishan County is located in the southeastern part of Gansu Province, with a total area of 909.97 km^2: 27 townships and 145 villages are under its jurisdiction, with a total population of 239,400, an average population density of 263 people/km^2, and a maximum population density of more than 600 people/km^2. The county is on the northeastern edge of the Qinghai–Xizang Plateau and the western Loess Plateau by the ancient Permian deposits NWW–SEE to the folded tectonic line. The terrain is high in the southwest and low in the northeast, the western part of the county is bedrock mountainous terrain, and the eastern and northeastern parts include the Loess gully region and river terraces. The county is located in the active tectonic zone of southeast Gansu Province, belonging to the northern section of China's north–south seismic zone, and is an important constituent area of the active Qilian Mountain massif on the northeastern edge of the Qinghai–Xizang Plateau.

The region is affected by the long-term extrusion of the Eurasian Plate and the Indian Plate, with strong neotectonic activities and many deep and large faults such as the Riyue Mountain Fault zone, the Laji Mountain Fault zone, the Guide Fault, and the Daotanghe River–Linxia south Mountain Fault zone in the region. Since 1949, two earthquakes of magnitude 6.0–6.9 and 14 earthquakes of magnitude 5.0–5.9 have occurred within 200 km of the epicenter, the largest being the 22 July 2013 Minzhang 6.6-magnitude earthquake.

Figure 1 shows the distribution of the rural residential survey sites in the high-intensity zone of the Jishishan *Mw* 6.2 earthquake. Among these, the survey sites located within the seismic intensity of VIII degree zone included the Dahe Community, Dahejia Village, Chenjia Village, Hanshanjia Village, Kexinmin Village, Kangdiao Village, Dadun Village, MeiPo Village, and Ganhetan Village of Dahejia Town; Shiyuan Village, Shenjiaping Village, Qinyin Village, and Xiaohongping Village of Shiyuan Town; Liuji Village, Gaoli Village, Yangwacun Village, Taojia Village, Tuanjie Village, and Xiaojia Village of Liuji Town; the Binhe Community, the Tuanjie Community, Qianling Village, and Zhongzhuang Village of Chuimatan Town; Liugou Village, Gaji Village, and Yuanjiashan Village of Liugou Town. Note the towns above belonged to Jishishan County, Gansu Province. Additionally, the Guanting Community, the Guanzhong Village, the Lajia Village, and the Zhaomuchuan Village in Guanting Town, the Qingyi Village, the Meiyi Village, the Nongchang Village, the Jintian Village, and the Caotan Village in Zhongchuan Township belongeing to Minhe County of Qinghai Province were also investigated, which were located in the seismic intensity VIII zone. Moreover, Fanjiagou Village of Shiyuan County, Zhangxiejia Village, Hejia Village, Lijiashan Village, and Lujiaozhuang Village in Guanjiachuan Town; Hulinjia Village, Zuojia Village, Gaoguan Village, and Diaoping Village in Hulinjia Town of Jishishan County; Badashan Village and Mei'er Village in Zhongchuan Town; Kasawa Village, Xiela Village, and Shengli Village in Xinger Town of Minhe County; Tashapu Village and Muchang Village in Qingshui Town of Xunhua County were located in the seismic intensity VII zone.

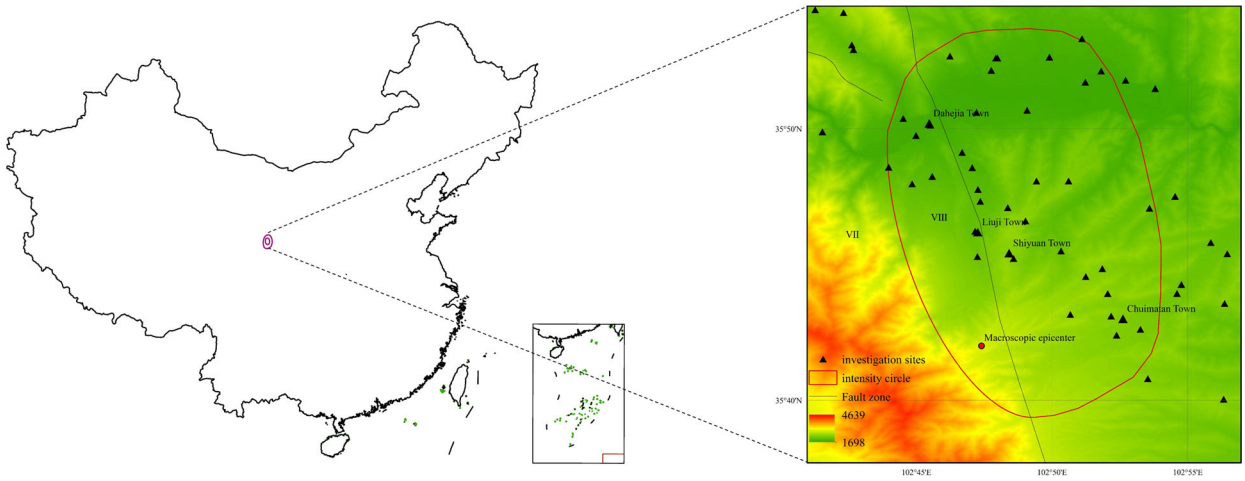


Figure 1. Distribution of the survey sites of the rural buildings in the high-seismic-intensity zone of the Jishishan M6.2 earthquake.

The survey sites were mainly located in the mountains and terraces region east of Jishishan Mountain, and the terraces of the Yellow River, the Liuji River, and the Chuimatan River. The types of house structures included civil structures, brick–wood structures, brick–concrete structures, and frame structures [27]. Among them, the housing structures of the Baoan nationality villages such as Dadun Village, Ganhetan Village, and Meipo Village; and the housing structures of the Tu nationality villages such as Meiyi Village, Zhaomuchuan Village, and Jintian Village were mostly mixed load-bearing. The front of the house has wooden columns and brick walls. The gables and cross walls are load-bearing brick walls or earth walls. Some gables include brick columns, and the roof is a system composed of

beams, rafters, purlins, and tiles, forming a complex mixed load-bearing structural system. The proportion of civil structure houses in the study area was about 5%, most of which were old houses constructed more than 30 years prior. The proportion of brick and wood houses was about 35%, and the proportion of brick–concrete houses was about 50%, which was divided into old brick–wood/brick–concrete houses and new brick–wood/brick–concrete houses, and most of them were not equipped with effective seismic-resistant structural measures. The frame-structure houses accounted for about 10%, mainly distributed in Dahejia Town, Shiyuan Town, Liuji Township, Chuimatan Town, Guanting Town, and Zhongchuan Town, mostly for public buildings such as schools and hospitals.

3. Characteristics of the Damage to the Rural Buildings

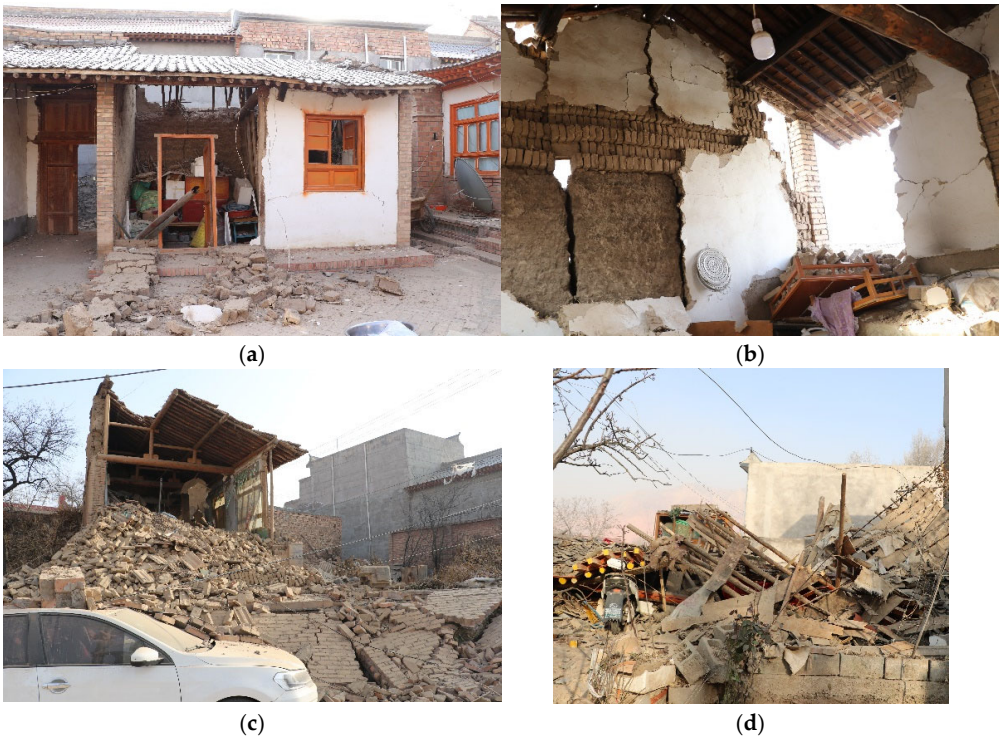
3.1. Characteristics of Seismic Damage to the Civil Structures

The civil structures in the high-seismic-intensity zone of the Jishishan *Mw* 6.2 earthquake mainly included adobe houses and beaten-cob constructions. The rural buildings were constructed more than 20 years ago, and most of them were used as storage rooms, kitchens, miscellaneous rooms, and other auxiliary rooms; however, a small amount were lived in by the elderly. Most of the civil structures destroyed or severely damaged in the earthquake were adobe masonry walls. The roofs were pent roofs or span roofs, which are made of wood and tiles, and the front wall was decorated with bricks. These were self-built by villagers, and no anti-seismic structural measures were set up.

Due to the different orientations of the rural houses, the direction of seismic wave propagation was perpendicular to the front wall or the transverse wall. Under the action of seismic shear force, the earthquake damage in the high-intensity area of this earthquake was characterized by wall cracks, the partial collapse of walls, or the total collapse of the buildings. The photos of typical earthquake damage are shown in Figure 2. Figure 2a shows an adobe structure with brick columns and adobe masonry walls at the four corners of the house, and the earthquake damage manifested itself in the partial collapse of the rear and front walls and the falling of the roof. Figure 2b shows a mixed load-bearing adobe structure of brick columns, adobe, and rammed-earth walls with brick columns at the corners of the house, a rammed-earth wall at a height of 1 m below the wall, adobe masonry wall at the top, and a span roof. The earthquake damage of the house manifested as longitudinal wall cracking, staggering, and partial collapse of the mountain wall. Figure 2c shows a civil adobe construction, with adobe masonry walls and a pent roof, with earthquake damage manifested as the collapse of the mountain wall and the partial collapse of the roof. Figure 2d shows an adobe and timber construction with earthquake damage manifesting as complete collapse. Considering the earthquake damage characteristics of adobe and timber constructions, the first issue is the inadequate connection between the adobe columns, walls, and intersecting walls. The roof is directly laid on the walls, adopting a 'hard-ridge beam on wall' configuration without effective connections. Secondly, the adobes are bonded using mud mortar, which results in insufficient strength of the bonding material used in wall construction. This, in turn, leads to severe seismic damage to adobe and timber structures. The primary causes of earthquake damage to adobe and timber structures can be summarized as follows: the lack of effective connections between load-bearing components, and inadequate strength of both the load-bearing walls and the bonding materials. Combined, these factors result in a lack of integral stability of the buildings, leading to poor seismic performance.

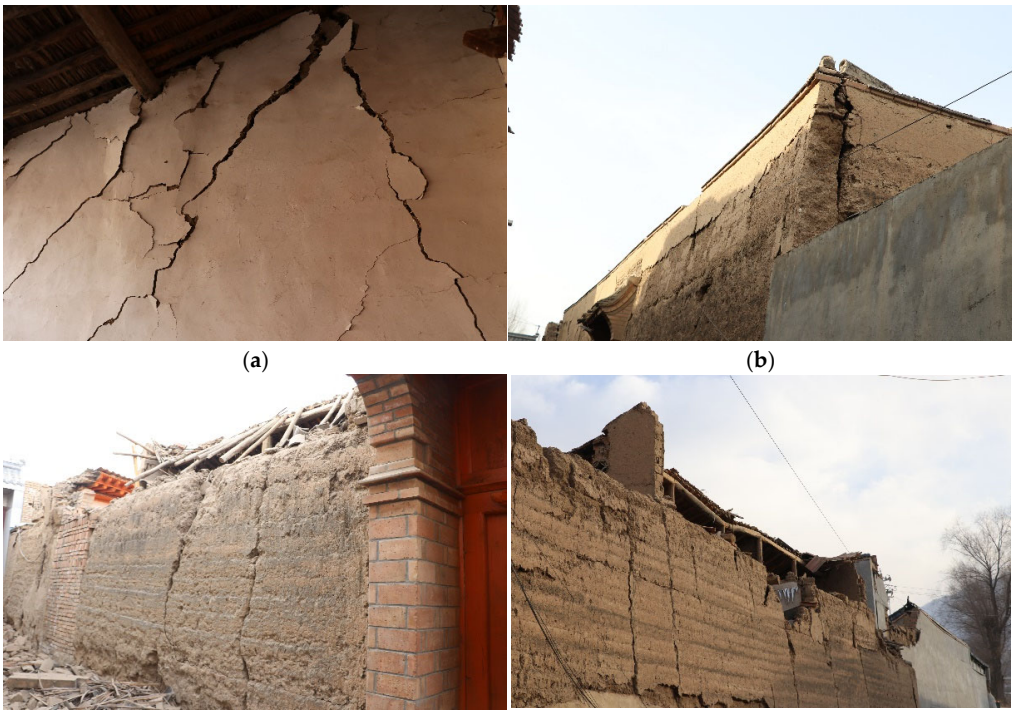
The typical earthquake damage to rammed earth wall structures in the high-intensity zones of this seismic event is illustrated in Figure 3. Because the strength of the rammed earth wall was better than that of the adobe wall, the earthquake damage to the rammed earth wall of civil structures was slightly milder, and the overall collapse of the wall was less common. In Figure 3a, the rammed earth wall with a 'hard-ridge beam on wall' timber structure exhibits multiple cracks beneath the ridge beams due to seismic forces. In Figure 3b, the seismic damage to the timber structure is manifested as the offsetting and outward buckling of the intersecting walls after they collided under the action of seismic

waves. Figure 3c shows damage where the roof collapsed, and sections of the wall at the top crumbled. As shown in Figure 3d, the damage included partial collapse of the rear wall's upper section and the dropping of the roof.



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

Figure 2. Typical earthquake damage photos of adobe civil structure. (**a**) Front wall collapsed. (**b**) Wall cracks and partially collapsed. (**c**) Pediment collapsed. (**d**) Total collapse.



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

Figure 3. Typical earthquake damage photos of civil rammed earth wall structure. (**a**) Wall cracks. (**b**) Vertical and horizontal wall flash cracks. (**c**) Roof collapse. (**d**) Partial collapse.

Summarizing the earthquake damage characteristics of rammed earth wall timber structures, these walls typically have a thickness of 30–50 cm and generally exhibit better load-bearing capacity compared to adobe walls. However, the primary cause of seismic damage lies in the inadequate connectivity among the various parts of the building: there is a lack of connecting measures between intersecting walls, as well as between walls and the roof. This results in insufficient strength at the connection points, leading to the formation of cracks, detachment, and even partial collapse of these connections under seismic forces.

3.2. Characteristics of Seismic Damages of the Brick–Wood Structures

The main load-bearing body of brick–wood structures is masonry brick walls and wooden roofs, which were widely distributed throughout the high-intensity area, with varying construction dates, both old and new brick and wood, all of which were self-built by the villagers, and did not include the setting of ring beams pr structural columns. Most of the newly built brick–wood structures were decorated with ceramic tiles veneers, most of which were for residential use. The earthquake damage to these buildings in the high-intensity area was characterized by eaves damage, wall cracks, partial collapse, or total collapse of the wall. Typical earthquake damage photos are shown in Figure 4. Figure 4a shows a brick–wood structure with a construction age of about 10 years. The prominent eaves were partially damaged, and tiles fell. Figure 4b shows a brick–wood structure built in the past five years, with tile veneer used for decoration, two slopes of the water–wood roof directly on the brick wall, with obvious cracks under the purlins under the effect of the earthquake and diagonal cracks appearing at the corners of the window and door openings as well as "X"-shaped cracks on the horizontal walls indoors. Figure 4c shows a new brick–wood structure. The collision of the longitudinal and transverse walls under the earthquake caused the longitudinal wall to flash out and partially collapse and the roof to partially collapse. Figure 4d shows an old brick–wood structure with a simple wooden roof built for more than 20 years ago. During the earthquake, the back wall collapsed, and the wooden roof collapsed.



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

(**c**) (**d**)

Figure 4. Typical earthquake damage photos of brick–wood structure. (**a**) Eaves damage. (**b**) wall cracks. (**c**) Partial collapse. (**d**) Total collapse.

Based on the analysis of the seismic damage performance of brick and wood structures, the old brick and wood structures were characterized by an early construction date, insufficient strength of the wall masonry materials and bonding materials, poor integrity of the walls, and heavy seismic damage, mainly local collapse or overall collapse. The main reason for the earthquake damage to the new brick timber structures was the lack of effective connection between the vertical and horizontal walls, roofs, and walls, resulting in cracks in the vertical and horizontal walls and cracks under the purlins. The unreasonable size of the opening of the building, the insufficient length of the overlap of the doors and windows, and the insufficient strength of the masonry mortar were the main causes of the cracks in the masonry wall. Based on the pursuit of beauty, the brick and wood structures have some overhanging eaves, which lead to an uneven layout of the house, so this prominent part is easily damaged under the action of earthquakes.

3.3. Main Earthquake Damage of Brick–Concrete Structure

The main bearing bodies of brick–concrete structures was the masonry brick wall, which were characterized by precast slab or cast-in-place concrete roof, single or two floors, accounting for about 10~20% of the total number of houses in high-intensity areas. The construction date was mostly after 2010, most of them did not set ring beams or structural columns, they were generally decorated with tile veneer, and most of them were residential houses. Typical earthquake damage photos are shown in Figure 5. Figure 5a shows a new single-layer brick–concrete structure with a cast-in-place concrete roof. Under the action of the earthquake, due to stress concentration, the four corners of the doors and windows had penetrating cracks. Figure 5b shows a two-story brick structure: the ground floor was set up with a foundation ring beam and an upper ring beam, the four corners of the house were set up with structural columns, and the second floor had no structural columns or ring beams. Due to the excessive opening of the second-floor house and the insufficient support force of the only brick column, the second floor of the door and windows seriously cracked, the wall was almost completely crushed, and the damage was serious: the building could no longer be used. Figure 5c shows a new, brick, cast-in-place concrete floor slab, not yet occupied. Because the transverse wall was perpendicular to the direction of seismic shear wave propagation, the overall strength of the brick wall was insufficient, with penetrating cracks and localized slumps in the transverse walls, which were severely damaged. Figure 5d shows a new two-story brick–concrete structure. Due to the insufficient strength of the building wall, the lack seismic structural measures, and the insufficient connection between the roof and the wall, the bottom and the second-story walls were generally cracked. The second-story back wall collapsed, the prefabricated slab roof fell, and the whole house almost collapsed.

Regard the comprehensive seismic performance of brick–concrete structures, brick–concrete structures are generally newer, but due to the differences in the level of economic development and household income, the lack of strength of the wall masonry and bonding materials was the main reason for the heavier seismic damage to the new brick–concrete structures. Secondly, the popularity of structural seismic measures such as ring beams and structural columns was not high, resulting in weak integrity of the houses and insufficient seismic performance, which were the reasons for the development of penetrating cracks and the collapse of the houses. Some of the buildings had ring beams and structural columns on the ground floor, yet the second floor featured only one large, open room in the central area. This floor used neither ring beams nor structural columns, while also pursuing an open-plan design with extensive use of floor-to-ceiling windows. The narrow spacing between windows, complex roof decorations, and excessive loading contributed to an interrupted vertical load transfer system and the uneven distribution of loads. Consequently, while the ground floor remained largely intact during earthquakes, the second floor sustained severe damage.



Figure 5. Photos of typical earthquake damage of brick–concrete structure. (**a**) Wall cracks. (**b**) Story two destruction. (**c**) Partial collapse. (**d**) Total collapse.

3.4. Main Earthquake Damage to the Frame Structure

The number of frame structures throughout the high-intensity zone was low, basically limited three- to four-story schools, hospitals and very few two-story residential housing. Two-story residential housing was intact, with earthquake damage mainly occurring in the form of falling wall cladding and chandeliers, with damage to fences and other decorations. Figure 6 shows a photograph of typical earthquake damage to a hospital, built about 15 years prior. Figure 6a shows the prevalence of interwindow wall cracks in this frame structure, which developed in all the walls of floors 1–3. Figure 6b shows that the door frame of the entrance on the ground floor of the hospital was crushed and deformed, and the glass was broken and fell off. Figure 6c shows the bottom wall bulging, deformation, cracks, and wall skin drop. Figure 6d shows the earthquake damage including wall cracks, door frame extrusion deformation, and falling in the office wall of the hospital. Figure 6e,f show that cracks appeared at the connection of the bottom vertical and horizontal walls, cracks in the wall under the beam, and dislocations between the wall and the beam.

From the analysis of the comprehensive seismic performance of the frame structures, the overall seismic performance of the frame structure was excellent; the main seismic damage occurred as window wall cracks, door and window opening cracks, longitudinal and transverse wall joints cracks, to doors and windows, and to other openings such as the location of the extrusion of deformation and frame beams. Infill wall stiffness was inconsistent, the beams and the wall vibration due to the seismic action of the different frequencies resulted in cracks and dislocations under the beams and the location of the dislocations. There were differences in the earthquake damage to each floor of frame structures, and the investigation of a four-story middle school building showed that fewer books fell to the ground in the classrooms on the first floor, and more and more books fell to the ground on the desks of the classrooms in the same location from the second floor to the fourth floor. The heaters on the first-floor and second-floor classrooms did not fall, the heaters on the third-floor classrooms fell slightly, and the heaters on the fourth-floor classrooms fell. It can be seen that the vibration amplitude increased with the increase in the floor level, and the vibration amplitude of the fourth floor was the largest, so the books

and heaters on the desk almost all fell. On the contrary, the earthquake damage on the first floor was the heaviest, and the earthquake damage decreased with the increase in the floor. The presumed causes were the load-bearing system on the first floor being subjected to the largest vertical load, and the earthquake effect intensifying the pressure on the vertical load, so the walls on the first floor had the largest cracks, and the tops of the framing columns showed the typical compression cracking damage phenomenon.



Figure 6. Photographs of typical earthquake damage to frame structures. (**a**) Wall cracks between windows. (**b**) Door frame extrusion deformation. (**c**) Wall bulging deformation. (**d**) Door frame deformation. (**e**) Longitudinal and transverse wall penetration cracks. (**f**) Cracks under the beam.

3.5. Rural Dwellings with Intact Seismic Structural Measures

In the high-intensity area of the Jishishan earthquake, there were also a small number of residential buildings built according to the local seismic fortification requirements. As shown in Figure 7a, the experimental building of Dahejia Middle School was a three-story frame structure built in the past five years, which had complete frame columns and frame beams. The building had good integrity: although it was located in the eight-degree intensity area, the frame structure and infilled wall of the house were basically intact after

the action of the earthquake. Only the wall had slight cracks and the wall skin dropped, which could be evaluated as basically intact. Figure 7b shows a two-story frame house, which was representative of the local residential buildings in terms of structural seismic measures. The seismic damage in this earthquake mainly included slight cracks and the falling of decorative tiles on the outer wall, and the rest of the components were not damaged. This showed the good seismic performance of the houses built according to the local seismic fortification standards. Therefore, it is recommended to select favorable sites, use qualified building materials, design reasonable layouts, and take necessary seismic measures according to the local seismic fortification requirements, so that the houses built will have good seismic performance and reduce the economic losses and casualties caused by earthquakes.



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

Figure 7. Photographs of typical earthquake damage to dwellings using anti-seismic construction measures. (**a**) Experimental middle school building. (**b**) Frame dwellings in Kexinmin Village.

4. Discussion

4.1. Characteristics and Mechanisms of Damage to Various Types of Houses

According to the 'The Chinese Seismic Intensity Scale' (GB/T 17742-2020) [28] and the 'Code for Seismic Design of Buildings' (GB50011-2010) [29], based on the field survey data, the proportion of the different damage degrees to the four types of residential structures (civil structure, brick–wood structure, brick–concrete structure, and frame structure) in the high-intensity area of Jishishan earthquake was calculated. The results are shown in Table 1.

Table 1. Damage ratio of typical residential structures in high-intensity area (%).

Structural Form	Number of Floors	Damage Level				
		Basically Intact	Minor Damage	Moderate Damage	Severe Damage	Destruction
Civil structures	1	5.1	9.6	22.1	46.8	16.4
Brick–wood structure	1	7.3	11.2	38.9	33.9	8.7
Brick–concrete structure	1	18.7	23.4	27.8	25.8	4.3
	2	10.9	21.4	31.5	29.6	6.6
Frame structure	≥2	56.4	40.8	2.8	0	0

Civil structures, brick–wood structures, and brick–concrete structures all used the load-bearing system of a wall, so there were many similarities in earthquake damage: wall 'X'-type shear cracks, cracks at the junction of vertical and horizontal walls, cracks in doors and windows, local collapse of walls, collapse, roof falls, and so on. There were four main reasons for earthquake damage: (1) The bearing wall strength was insufficient. The architectural form of the civil structures in the high-intensity areas was more complex and

changeable, with the main structures including hybrid rick column–adobe wall bearing load, front wall wooden column with the remaining adobe wall bearing load, the lower part of the rammed earth wall and the upper part of the adobe wall bearing load. The general adobe wall masonry material was raw adobe, the bonding material was mud, and the strength of the masonry material and the bonding material was poor, resulting in insufficient strength and ductility of the bearing wall. Under the action of the earthquake, the walls were prone to brittle failures, such as cracks and collapse. (2) Effective connections were lacking. In the high-seismic-intensity area, there was no effective connection between the wooden column/brick column and the wall, the rammed earth wall and the adobe wall, the vertical and horizontal walls, as well as the bearing wall and the roof of the civil brick–wood structures and brick–concrete structures. Due to the differences in materials, the vibration amplitude of the brick column/wooden column, the rammed earth wall/adobe wall, the wooden roof, and the brick wall/adobe wall were different under the action of the earthquake, and the vibration directions of the vertical and horizontal walls were also different. Therefore, cracks, roof falling, and even wall flashing easily occurred at the junction of the brick column/wooden column and the rammed earth wall/adobe wall, the wooden roof and the brick wall/adobe wall, and the vertical and horizontal walls. (3) Earthquake-resistant construction measures were lacking. In the high-intensity zone, the civil structures and the brick–wood structures did not have earthquake-resistant structural measures such as ring beams and structural columns, and some of the two-story brick–concrete structures only had ring beams and structural columns on the ground floor but not on the second floor. The absence or incompleteness of the seismic-resistant structural measures such as ring beams and structural columns led to the weak integrity of the houses, so that the two-story houses with missing seismic-resistant structural measures were crushed and damaged under the action of the earthquake, and the earthquake damage, such as the outward flashing of the walls of the adobe structure and the brick structure and the collapse of the walls, was more serious. (4) The housing layouts were not reasonable. In recent years, the self-built brick–wood structures and brick–concrete structures have involved large bays and large windows. Some brick–concrete structures only had one large bay on the second floor, and all four walls were floor-to-ceiling windows. This method made the wall between windows too narrow, and the strength of the force transmission system was seriously insufficient. The narrow wall between windows was prone to brittle failure under earthquake action: First, cracks or cuts directly led to the deformation of doors and windows and the collapse of houses. Second, due to the lack of precipitation and poor water resources, some civil structures and brick–wood structures adopted a sloped water roof. Compared with the two-slope water roof, the center of the house with a one-slope water roof is higher and the load distribution is uneven, so the earthquake damage to the houses with a one-slope water roof was heavier. The third included damage to the part of the whole house, such as the parapet wall and the eaves. Due to the whiplash effect of the earthquake, the seismic damage to the parapet wall and the eaves was heavier. (5) The decorations are too heavy. To be beautiful, tiles are pasted on the front wall of the house, decorative wood carvings are pasted under the eaves, reinforced concrete is used to pour the roof and door of the bucket arch, and all-glass outer corridors are added. These decorations first increase the load of the load-bearing system, and, secondly, the connection with the house is insufficient. Therefore, under the action of the earthquake, the decorations easily separated from the main body of the house, deformed, dropped, or even dumped, which aggravated the earthquake damage to the house.

For post-disaster new residential buildings, an effective way to improve the seismic resistance of civil structures is to improve the integrity of the structures, including optimizing the bonding materials of civil structures, brick–wood structures, and brick–concrete structures, enhancing the tie between vertical and horizontal walls, and vigorously promoting the use of seismic measures such as ring beams, structural columns, and lightweight roofs. For residential buildings that need to be repaired and did not adopt seismic structural measures after the earthquake, measures such as adding external frames, adding tie

measures to vertical and horizontal walls, and adding brick stacks to long vertical walls can effectively improve their seismic performance.

4.2. The Influence of Site Conditions on the Earthquake Damage to Buildings

Wang et al. [30–32] discussed the relationship between amplification factors and site conditions from the aspects of loess topography and thickness, and they proposed that the amplification effect positively correlated with loess thickness and slope height. Wang et al. [33] proposed that the damage and dynamic response of seismic waves to buildings at the top of the slope were more obvious than those at the bottom of the slope. The distance between Shenjiaping Village and Gaoli Village in Shiyuan Town is about 800 m. Shenjiaping Village is on the hillside, and Gaoli Village is at the bottom of the hill. The earthquake damage to Shenjiaping Village was more serious than that to Gaoli Village, as shown in Figure 8. Figure 8a shows a brick–concrete structure in Gaoli Village, Liuji Township, which was built in 2007. The main seismic damage was the deformation of the window frame and the partial dislocation of the gable. Figure 8b shows a brick–concrete structure built in 2016 in Shenjiaping Village, Shihao Township, with earthquake damage manifesting mainly in the external flashing of the hill wall and severe cracks in the wall.



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

Figure 8. Photographs of earthquake damage to brick structures at different sites. (**a**) Gaoli Village. (**b**) Shenjiaping Village.

The sloping site enhanced the reflection of the seismic waves, and the sedimentary loess layer had an amplification effect on seismic waves, which increased the duration and amplitude of the seismic waves. According to the records from the seismic stations [34], the peak ground motion in the vicinity of Dahejia Town, Liuji Township, and Shiyuan Town was 0.905–1.071 *g*, which was greater than the peak acceleration of intensity VIII in this area. The above reasons led to the houses in Dahejia Town, Liuji Township, and Shiyuan Town being seriously damaged.

The seismogenic fault of this earthquake was the reverse type. Gao Mengtan [35] believed that the rupture extended from the source to the NWW direction and terminated near Dahejia Town. From Liugou Township to Dahejia Town, the thrust fault plane had a very large destructive force in the strong vibration area, especially with high-frequency ground motion. The upper plate effect of the fault caused severe damage to the structures located on the upper plate site. Dahe Community, Chenjia Village, Hanshanjia Village, and Kangdiao Village, which also belong to Dahejia Town, are located on the hanging wall of the seismogenic fault. Ganhetan Village, Meipo Village, and Dadun Village are located on the footwall of the seismogenic fault. According to the 'Gansu Jishishan *Mw*6.2 earthquake intensity map', in this earthquake intensity assessment, Dahe Community, Chenjia Village, Hanshanjia Village, and Kangdiao Village were VIII-degree areas of the earthquake, and the buildings were seriously damaged. Ganhetan Village, Meipo Village, and Dadun Village

were in the VII-degree area of the earthquake, and the damage to their buildings was less than that in the VIII-degree area.

4.3. The Influence of Seismic Wave Propagation Direction on Seismic Building Damage

According to "the '5·12' Wenchuan earthquake building damage analysis and countermeasure research report", the layout and orientation of the building were always considered according to the specific site conditions. When the weak seismic direction of the building (generally lateral) was consistent with the vibration direction of the seismic wave, the seismic damage of the building was aggravated. The rupture direction of the seismogenic fault of this earthquake was NW, so under the same conditions, the damage to the east–west-oriented houses was more serious than that to the north–south-oriented houses. Figure 9 is a brick–wood structure in Shenjiaping Village, Shiyuan Town. The orientation of the structure was from north to south. The seismic damage of the diaphragm wall and the longitudinal wall was consistent with the conclusions of this study. The cross-wall of the brick–wood structure was east–west, which was consistent with the direction of the seismic wave propagation. As shown in Figure 9a, the cross-wall had 'X'-type shear cracks and had 2~5 cm dislocations owing to the earthquake action. Figure 9b shows a longitudinal wall, and the earthquake damage was less than that to the diaphragm wall, which was an oblique crack.



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

Figure 9. Photographs of vertical and horizontal wall damage. (**a**) Mirror direction: north east. (**b**) Mirror direction: northwest.

5. Conclusions

This field investigation of the Jishishan *Mw*6.2 earthquake showed that the residential buildings with typical structures in the high-intensity area had the following characteristics:

(1) The seismic damage to civil structures and brick–wood structures was similar. In general, these two structures accounted for 70–80% of the residential buildings, which were self-built by the residents. Generally, no seismic structural measures were set up, and the wooden roofs were mostly made of hard-ridge beams with an on-wall construction style. The architectural forms of the adobe civil structures were more complex. Mixed load-bearing walls of the wooden column/brick column–adobe walls and mixed load-bearing walls with the lower half being rammed earth walls and the upper half being adobe walls were more common. Therefore, the seismic damage to adobe civil structures was more serious than that to rammed-earth civil structures. The older residential buildings were mainly severely damaged and destroyed. The main seismic damage was wall-penetrating cross-cracks, the local collapse of load-bearing walls, the collapse of gables, or overall collapse. The residential buildings that were less than 15 years old were mainly moderately damaged and seriously damaged. The earthquake damage mainly included cracks under the purlin, roof falling, wall cracks, and local collapse of the load-bearing wall.

(2) Brick–concrete structures accounted for 20~25%, and the roofs were of two kinds: precast slab and cast-in-place slab. Before 2008, there were no anti-seismic construction measures generally. In recent years, most of the two-story brick–concrete structures built had ring beam construction columns on the bottom floor. In the high-intensity area, these kinds of residential buildings mainly experienced medium damage and serious damage. The main seismic damage included wall cracks, cracks in doors and windows, falling of prefabricated slab floors, and destruction or partial collapse of the second-floor wall of residential buildings with discontinuous seismic structural measures.

(3) The frame structures was mainly used for hospitals, schools, and other key fortification buildings, with generally 3~4 stories. Dwellings accounted for about 5%, mostly two floors, and were basically intact. The earthquake damage to hospitals and schools was mainly caused by damage to the non-load-bearing components: cracks in the window wall/diaphragm walls, cracks under the beams, bulging and peeling of the walls, deformation of doors and windows, and falling of chandeliers/heaters.

(4) The overall stiffness of the load-bearing wall was low due to the insufficient strength of the building materials and bonding materials. The lack of effective connection between the vertical and horizontal walls, as well as the load-bearing wall and the wooden roof; the low utilization rate of seismic structural measures or their incomplete setting; the unreasonable layout of the houses; and the heavy decoration were the main reasons for the heavy earthquake damage to these civil structures, including brick–wood structures and brick–concrete structures.

(5) The amplification effect of ground motion and the hanging wall effect of the fault caused by the thick loess basin and slope site were the main reasons for the aggravation of the seismic damage to the residential buildings. The seismic damage to the walls, which was vertical or nearly vertical to the propagation direction of the ground motion, was more serious.

(6) The data obtained in this study and the comparison of the seismic damage performance of the buildings with and without seismic structural measures according to the local seismic fortification requirements have a positive effect on the local promotion of seismic fortification codes. The results revealed the excellent seismic capacity of buildings built in accordance with the seismic fortification codes obtained from the data. This study has reference significance for local site selection, building structure selection, plane layout, increasing seismic structural measures, and implementing building reinforcement methods in post-disaster reconstruction projects, which will be conducive to promoting the application of seismic fortification specifications in rural areas.

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