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Building damage in Dujiangyan during Wenchuan Earthquake

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Abstract: A field damage survey of 1,005 buildings damaged by the Wenchuan Earthquake in Dujiangyan City was carried out and the resulting data was analyzed using the statistical method. It is shown that buildings that were seismically designed achieved the desired seismic fortification target; they sustained less damage than the non-seismically designed buildings. Among the seismically designed buildings investigated, RC frame buildings performed the best in terms of seismic resistance. Masonry buildings with a ground story of RC frame structure were the second best, and masonry buildings performed the worst. Considering building height, multistory buildings sustained more severe damage than high-rise buildings and 2- and 3-story buildings. Compared to residential buildings, public buildings, such as schools and hospitals, suffered more severe damage.

Keywords: Wenchuan Earthquake; Dujiangyan; building damage; seismic intensity; field survey

1 Introduction

Dujiangyan is a city located in the northwest area of Chengdu, and famous for its Dujiangyan Irrigation Scheme. The irrigation scheme has a long history of 2,260 years in ancient China, and operated very well until today. The city is 21 km away from the epicenter and its seismic intensity during the earthquake was about VIII-IX (on the Chinese seismic intensity scale), while its original seismic fortification intensity was VII. Buildings in the city can be divided into three groups. Group A includes non-seismically designed buildings constructed prior to the 1970s such as ancient architectures and houses owned by citizens. The main structure types of Group A are brick-wood and timber. Group B includes buildings built in the 1980s that either do not consider earthquake forces, or only consider minor forces. The main types of structures in Group B are masonry and masonry with a ground story of RC frame. Group C includes buildings built after the 1990s that were built according to seismic design specifications. The main structure types in this group are masonry, masonry with a ground story of RC frame, and RC frame structure. There are few mid-high-rise buildings in Group C. For some of the masonry buildings with a ground story of RC frame, the ground story consisted of a frame structure with a storefront and masonry wall in the rear.

The field survey of buildings was conducted mainly in the urban areas of Dujiangyan, including parts of the suburbs, i.e., Xingfu, Juyuan and Yutang Towns. A total of 1,005 buildings were investigated in 10 randomly selected survey sites, and around 100 buildings in each surveyed site were included (see Fig. 1).

The earthquake damage grade of buildings was evaluated in the field survey according to the standard *Grade Classification of Earthquake Damage for Buildings and Special Structures* (GB/T18208.3-2000). In the statistical analysis, the damage index of buildings is used as a quantitative measure of the earthquake damage grade as shown in Table 1.

The damage to timber structures includes: tile slipping from the roof, wall collapse but frame standing, roof truss damage and building collapse. The damage to masonry structures includes: wall cracking, tie column shear, staircase fracture, collapse of top structures of the building, and the collapse of the entire building. The damage to masonry structures with a ground story of RC frame includes: frame beam and column damage, bottom frame inclining, bottom masonry wall cracking, and building collapse. Finally, the damage to RC frame structures includes: infill wall cracking and falling off, and slight damage to some frame beams and columns.

Some representative pictures of the surveyed buildings will be shown in Figs.2-17 in the next section.

2 Comparison of buildings with and without consideration of seismic action

The number of buildings in the three groups and their calculated average damage indexes are listed in Table 2.

The damage ratio for a given damage grade in

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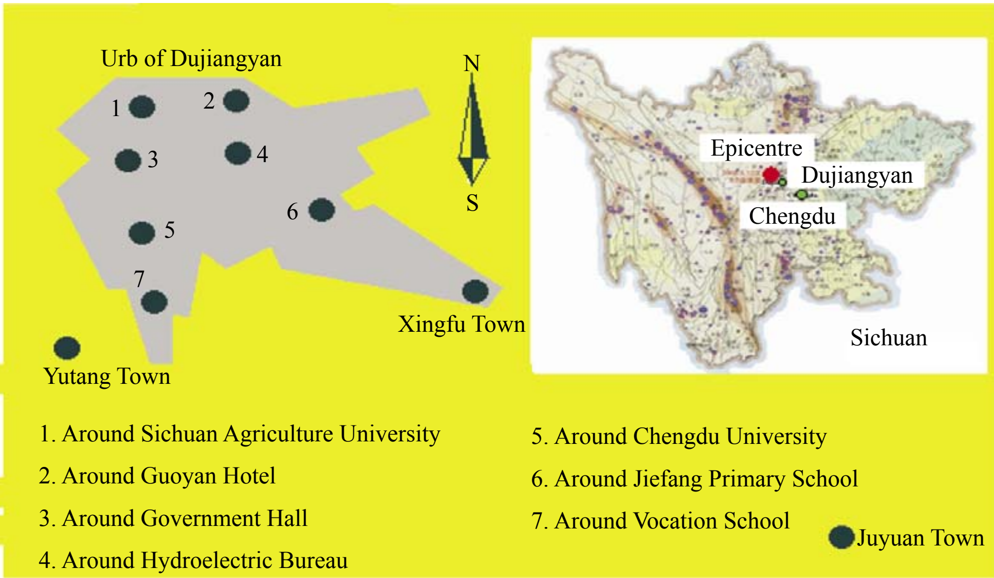

Fig. 1 Distribution of the surveyed sites (left) and the position of Dujiangyan in Sichuan Province (right)

Table1 Damage grade and damage index of buildings

Damage grade	Intact	Slight	Moderate	Severe	Collapse
Damage index	0-0.1	0.1-0.3	0.3-0.55	0.55-0.85	0.85-1.0

Fig 2 Two-story brick-wood residential building in Hongzhuangjie District (Group A, roof collapsed)

Fig. 3 One-story brick-wood hut (GroupA, moderately damaged)

Fig. 4 Brick-wood residential building in Yangcha Village (Group A, collapsed)

Fig. 5 Timber structure in Erwangmiao scenic spot (Group A, roof damaged, inclined)

Fig. 6 Masonry building in Kuiguang Street (Group B, moderately damaged)

Fig. 7 Masonry structure, students' dormitory of Chengdu University (Group B, top collapsed)

Fig.8 Masonry building with a ground story of RC frame structure in Hehuachi District (Group B, seriously damaged)

Fig. 10 Masonry residential building in Kuiyuandongjie District (Group B, collapsed)

Fig. 9 Masonry structure in Hehuachi District (Group B, collapsed)

Fig. 11 Inpatient department of Hospital of Traditional Chinese Medicine (Group B, collapsed)

a given building group is defined as the ratio of the number of buildings within the damage grade to the total number of buildings in the group. Results of the calculation of the damage ratio are plotted in Fig. 18 for the three building groups.

Note that the damage ratio for the "collapse" damage grade (or, for simplicity, the "collapse ratio") for Group A is significantly higher than for the other two groups, and is only 1% for Group C. Group B has the highest heavy damage ratio of the three groups, which is only 17% for Group C. In addition, the buildings of Group C exhibit the largest damage ratios in the slight and negligible damage grades, reaching 21% and 46%, respectively. The various damage ratios of three Groups of buildings are in agreement with the results of the average damage index, as shown in Table 2.

As stated above, the seismic intensity in Dujaingyan City was about VIII-IX, while the seismic fortification intensity was only VII. Therefore, it can be concluded that for buildings that were well designed according to the *Code for seismic design of buildings* (GBJ11-89) or its revised version (GB50011-2001) and were well-constructed, the seismic fortification target of "no collapse under a strong earthquake" was achieved.

Seismically designed buildings had a reduced number of casualties, a ratio of slight damage and negligible damage of over 50%, and could remain in use after some structural repair and seismic strengthening.

Fig. 12 Masonry building with a ground story of RC frame in Kuiyuanxijie District (Group B, seriously damaged)

Fig. 13 RC frame structure, Guoyan Hotel (Group C, moderately damaged)

Fig. 14 Masonry residential building in Gaoqiao District (Group C, negligibly damaged)

Fig. 15 Masonry laboratory of Juyuanzhen Middle School (Group C, seriously damaged)

Fig. 16 Masonry building of Tazhonglianzhong School (Group C, moderately damaged)

Fig. 17 Tiandiren Hotel (Group C, top building collapsed)

Thus, they played an important role in reducing the economic loss and allowing the social order to recover.

Note also that the ratio of severe damage is much higher than collapse for Group C, which demonstrates the effectiveness of seismic detailing to prevent building collapse, and shows the importance of further research and implementation of performance-based seismic design measures. These measures can help to mitigate the losses that resulted from the severe damage to buildings designed according to the current design code.

Table 2 Basic parameters of different building groups

Group	A	B	C	Total
Building number	230	224	551	1005
Average damage index	0.62	0.49	0.23	0.38

3 Statistical analyses of seismic capacity of seismically designed buildings

In sampling seismically designed buildings, 243 (1 to 7-story) were masonry structures, 119 (2 to 7-story) were masonry structures with a ground story of RC frame, and 139 (1 to 13-story) were RC frame structures. The height distribution of these buildings is plotted in Fig.19.

3.1 Building type effect

From the analysis of data from the field surveys, the damage ratios of different damage grades of three different types were obtained as shown in Fig.20. Note that the average damage index of masonry structures is 0.34, masonry structures with a ground story of RC frame is 0.30, and RC frame structures is only 0.15.

To exclude the influence of the building height, the analysis was restricted to 5-story buildings, and the results are shown in Fig. 21. Note that the average damage indexes of the masonry structures, masonry structures with a ground story of RC frame, and frame structures are 0.38, 0.35 and 0.21, respectively.

The above two analyses result in the same conclusion. That is, the RC frame structure has the best seismic resistance, followed by the masonry structure with a ground story of RC frame. The masonry structure offers the worst performance in an earthquake of this intensity.

3.2 Building height effect

Masonry structures and masonry structures with a ground story of RC frame were studied to determine the effect of the building height. The average damage index of the 6 and 7-story and the 2 and 3-story buildings were calculated, respectively, and the results are shown in Table 3.

Note that taller buildings had lower seismic resistance for both building types under consideration. In addition, The field survey found that the damage to mid-high-rise buildings, which had only a small number in the affected area, was no more severe than moderate.

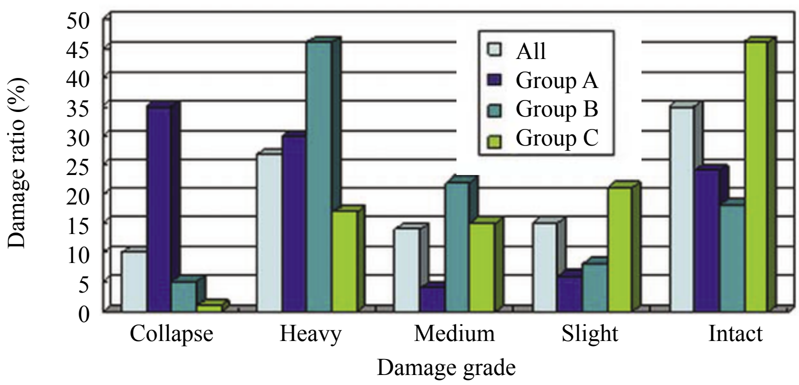

Fig. 18 Damage ratio of buildings

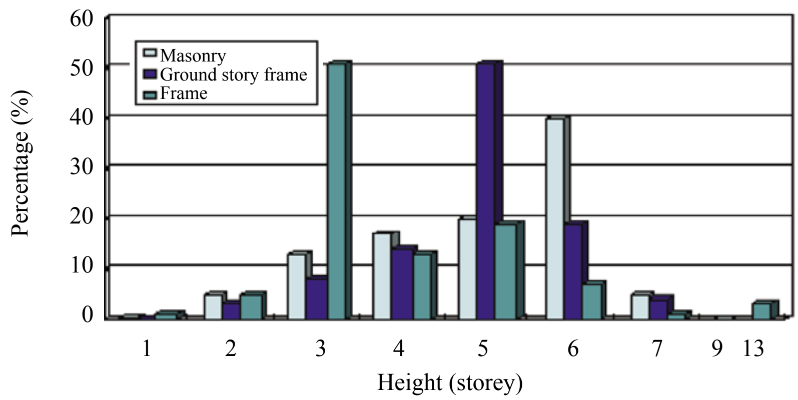

Fig. 19 Height distribution of seismically designed buildings

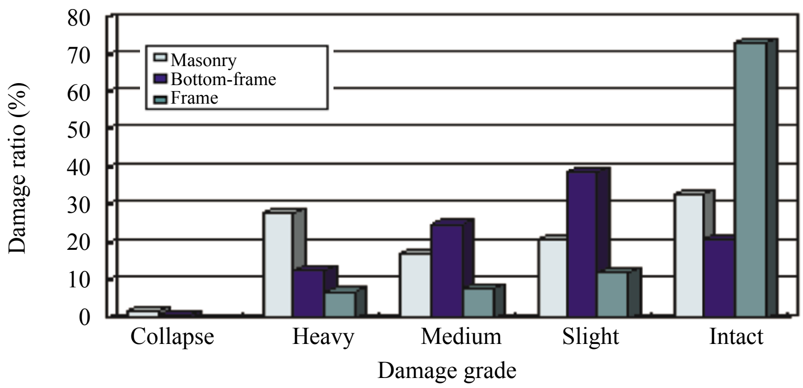

Fig. 20 Damage ratios of seismically designed buildings

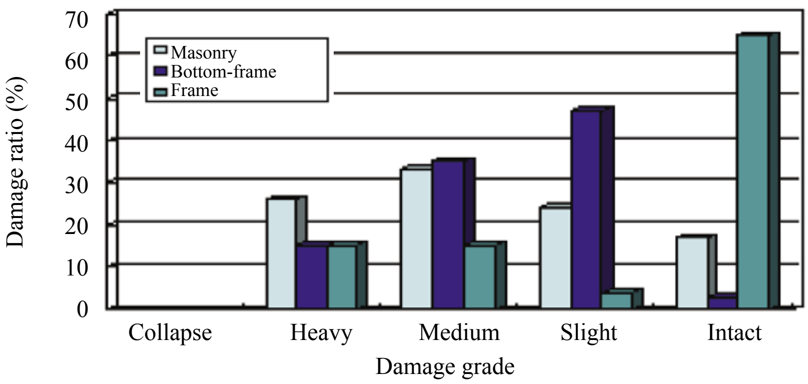

Fig. 21 Damage ratio of 5-story seismically designed buildings

Table 3 Damage indices of various story buildings

Building type	Story number	Average damage index
Masonry structure	2 and 3	0.18
	6 and 7	0.41
Masonry with ground story of RC frame	2 and 3	0.19
	6 and 7	0.31

3.3 Building's function effect

To explore the effect of the building's function, the analysis was limited to two categories of masonry buildings, i.e., residential buildings and public buildings, of which the latter includes schools, hospitals and other public buildings. The distribution of their damage ratios is plotted in Fig. 22. Note that the average damage indexes of residential building and public building are 0.27 and 0.37, respectively.

Note that the damage to public buildings was more extensive due to the large width of the rooms, which often meant that there were fewer shear walls in the unit length of the building.

4 Conclusion

Earthquake damage to buildings is very different and its mechanisms are complicated. There are many factors that contribute to this damage, such as the ground motion characteristics, site conditions, structural dynamic characteristics, design strategy, construction quality, and so on. In this paper, the general characteristics of building damage were statistically analyzed based on 1,005 buildings surveyed in and near Dujiangyan City during the Wenchuan Earthquake. Some preliminary conclusions are as follows.

(1)The validity and necessity of structural seismic design has once again been demonstrated by the Wenchuan Earthquake. Seismically designed buildings exhibit much higher seismic resistance than non-seismically designed buildings. Seismic fortification of buildings has a substantial significance in reducing casualties and economic losses.

(2) For buildings designed with a seismic fortification intensity VII according to the *Code for seismic design of buildings* (GBJ11-89 or GB50011-2001), less than 20%

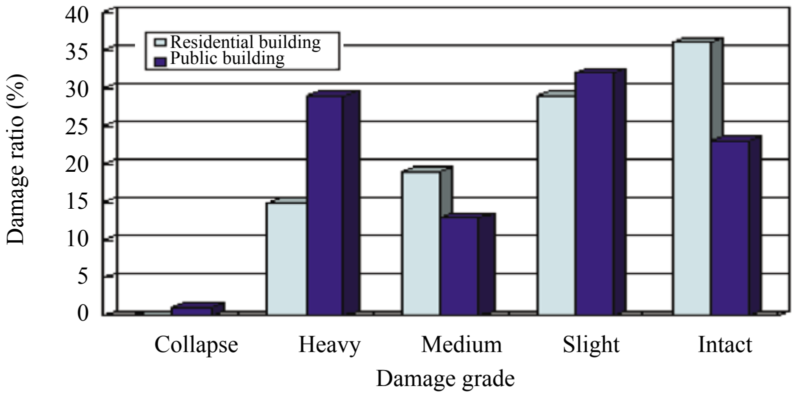

Fig. 22 Damage ratios of masonry buildings with various function

collapsed or were seriously damaged, and more than half were slightly or negligibly damaged. Considering that the seismic intensity in Dujiangyan city was about VIII-IX during the earthquake, this shows that the seismic fortification target was achieved, and that the current seismic fortification level of buildings at a minimum level is reasonable.

(3) For seismically designed buildings of different structural types, the RC frame structure showed the highest seismic resistance, and masonry structures with and without a ground story of RC frame take second place. For masonry structures with and without a ground frame story, the higher the building, the more severe the damage. The damage grade of mid-high-rise RC frame structures existing in the affected areas was at the medium grade or lower.

(4) For masonry structures with and without a ground frame story, the damage to public buildings, such as schools and hospitals is more severe than to residential buildings due to fewer seismically resistant walls. For these types of buildings where many people congregate, enhancing the seismic fortification level or adopting RC structure should be considered.

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