REGIONAL SEISMIC DAMAGE SIMULATION FOR THE BUILDINGS IN THE EPICENTER AREA OF 2014 LUDIAN EARTHQUAKE

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Abstract

A M6.5 earthquake struck Ludian County, Yunan Province, China on August 3, 2014. The earthquake was proved to be very destructive, although the magnitude is moderate. The seismic damage of buildings predicted by the conventional intensity-based damage probability matrix method differs significantly from the actual damage. To better simulate the seismic damage of urban areas by taking full consideration of the seismic resistances of buildings and the features of ground motions, an improved seismic damage simulation method based on multiple-degree-of-freedom concentrated mass shear (MCS) model and nonlinear time-history analysis (THA) is proposed. The method has the following advantages: (1) easy-to-construct building model; (2) reliable nonlinear parameter determination method; and (3) high computation efficiency. Only the building attribute data (i.e., year of construction, number of stories, height, design intensity and structural type) are needed as input for the automatic model generation and parameter determination. Based on extensive experimental and analytical results, the parameter determination method for three types of most widely used multi-story buildings (i.e., reinforced concrete frame structures, reinforced masonry structures and unreinforced masonry structures) is proposed, the reliability of which is verified by comparing with the experimental results of individual structures. Powered by the GPU-based high-performance computing, the simulation can be performed with very high efficiency, which is sufficient for regional damage simulation of large urban areas. With the proposed method, the seismic damage of buildings at the epicenter area of 2014 Ludian Earthquake is simulated. The method can better consider the capacity of each building on each floor and the time/spectral domain characteristics of the ground motions. In consequence, the prediction results agree well with the actual damage. This research may provide a reference for the vulnerability analysis of multi-story buildings in pre-earthquake scenario and the fast seismic damage assessment in post-earthquake scenario.

Keywords: regional seismic damage simulation, multi-story building, multiple-degree-of-freedom shear model, nonlinear time-history analysis

1. Introduction

Modern cities are becoming integrated systems that consist of a high density of population and buildings. Once they are hit by earthquakes, the damage or collapse of buildings will result in huge economic losses and casualties. Being one of the major structural systems in cities, multi-story buildings occupy a large proportion of seismic damage and collapse in previous earthquakes, e.g., 1994 Northridge earthquake (US) [1], 1995 Kobe earthquake [2] and 2008 Wenchuan earthquake [3, 4]. Therefore, an accurate and efficient regional seismic damage prediction method is required to assess the seismic damage of multi-story buildings in order to mitigate the earthquake disasters in modern cities.

Existing regional seismic damage prediction methods include the following: (1) the damage probability matrix method [5], (2) the capacity spectrum method [6, 7] and (3) the time-history analysis (THA)-based method [8, 9]. The damage probability matrix method is developed based on the statistical damage of different types of structures in previous earthquake events. However, this method is sometimes not reliable for some earthquakes (e.g., extremely strong earthquakes) or regions for which limited historical building damage statistics are available. The capacity spectrum method adopts single-degree-of-freedom (SDOF) building models and pushover analyses to predict seismic damage. The capacity spectrum method can well represent the global strength and ductility of buildings with moderate computational workload, and has been widely used in previous studies [10, 11]. Nevertheless, this method cannot easily represent the concentration of damage to different stories (e.g., soft-story failure mode) and the time-domain properties of ground motions (e.g., the velocity impulse of ground motions) [9]. In contrast, the THA-based method adopts multiple-degree-of-freedom concentrated mass shear (MCS) models and nonlinear THA to predict seismic damage, which can fully represent the time/spectral domain characteristics of ground motions and the nonlinear characteristics of buildings [8, 9]. Thus, the THA-based method is more accurate in theory and can be a very good option for regional seismic damage prediction.

Despite its larger computational workload, the THA-based regional seismic damage prediction is feasible due to recent advances in computer science. For example, Yamashita et al. [12] performed the regional seismic damage prediction for Tokyo urban area using the THA-based regional seismic damage prediction based on a super computer. To avoid the high maintenance costs of super computers, Lu et al. [9] simulated a medium-sized urban area of 4000 buildings in China using the THA-based regional seismic damage prediction powered by Graphic Processing Units (GPUs).

On August 3rd, 2014, a M6.5 earthquake occurred in Ludian County, China. Fortunately, the accelerograph at the epicenter, Longtoushan Town, recorded the ground motion of the main shock. In addition, reconnaissance teams collected the detailed seismic damage and attribute data of buildings in the Longtoushan Town [13]. These data can be used to validate the MCS building models for regional seismic damage prediction.

Based on the above background, this work proposes a parameter determination method and the corresponding damage assessment method for the MCS building models of widely used multi-story structures, including reinforced concrete (RC) frames, reinforced masonry (RM) structures and unreinforced masonry (URM) structures. The proposed parameter determination method is examined by comparing its results with the experimental results of three individual buildings. Subsequently, the proposed THA-based regional seismic damage prediction is used to estimate the seismic damage of Longtoushan Town during 2014 Ludian earthquake. The prediction results agree well with the actual damages which are more accurate than the results obtained by the damage probability matrix method. This research will provide a reference for the seismic damage prediction of large urban areas.

2. Methodologies

2.1 Framework

The framework and methodologies of the THA-based regional seismic damage prediction are illustrated in Fig.1. The framework mainly consists of three modules (shown as the blue boxes in Fig.1): (1) Parameter determination: The building attribute data (e.g., year of construction, number of stories, height, design intensity, structural type, etc.) obtained from the geographic information system (GIS) are used at this stage to generate the MCS model of each building and calibrate the parameters of the inter-story hysteretic models, through a simulated design procedure and extensive statistical analyses; (2) Nonlinear THA: Selected ground motions are input into the MCS models to implement the THA, and the engineering demand parameters (EDPs) (e.g. inter-story drifts and peak floor accelerations) are generated; (3) Damage assessment: Based on the corresponding damage criteria of each structural type and the computed inter-story drifts, the damage states for different stories of each building are determined. Stages (1) and (3) will be presented in detail in this study, and a detailed description of Stage (2) can be found in the previous work of the authors [9].

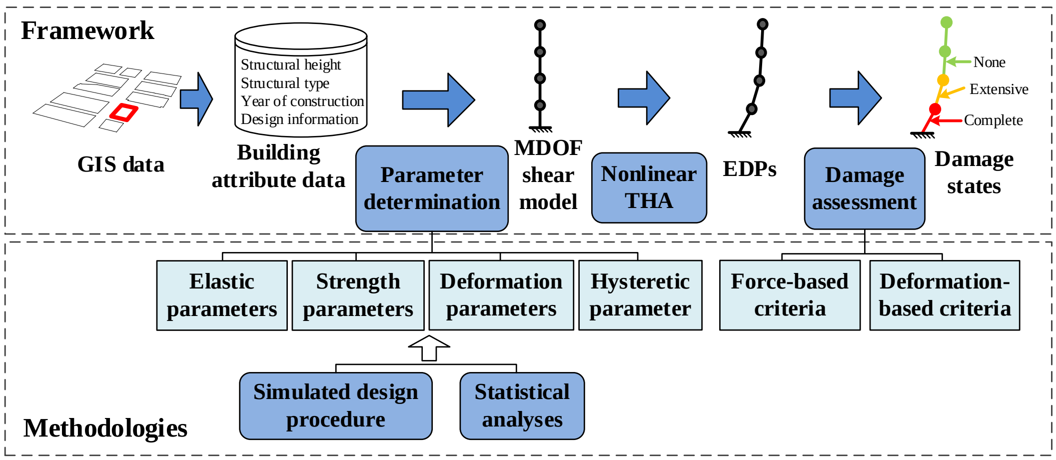
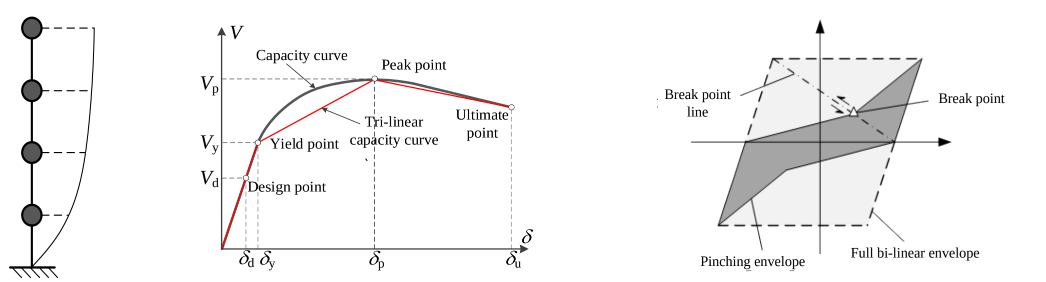


Fig. 1 – The framework and methodologies of the THA-based regional seismic damage prediction

2.2 MCS model

According to the “Chinese code for design of civil buildings” [14], multi-story buildings denote buildings less than 7 stories or 24 m. In China, most of such buildings are masonry structures or RC frame structures, which are widely used as residential or office buildings. Therefore, this work mainly focuses on these two types of multi-story buildings.

Considering the attribute data of each building is limited and the number of building in urban area is huge, the seismic response prediction model of buildings should be relatively simple. In this study, the MCS model (as shown in Fig.2) is adopted. Existing researches proved that the MCS model can well capture the nonlinear properties of multi-story buildings, predict the EDPs on each story and consider the damage concentration on different stories [9, 15].



(a) MCS model (b) Tri-linear backbone curve (c) Single parameter hysteretic model

Fig. 2 – The MCS model

A tri-linear backbone curve is used herein to simulate the inter-story nonlinear properties (Fig.2b) [16]. Many previous studies showed that the tri-linear backbone curve model can accurately represent the inter-story behavior of a structure [16, 17] with acceptable modeling complexity and computational accuracy. Due to limited amount of detailed building information, a single parameter hysteretic model proposed by Steelman and Hajjar [18] is adopted herein (Fig.2c).

3. Parameter determination

The parameter determination method includes the determination of elastic parameters, backbone curve parameters and hysteretic parameter, as illustrated in Fig.3.

Due to the limited information of the building attribute data, the simulated design procedure and statistical analyses are used. The simulated design procedure follows building design codes to estimate the design strength (V_d) of each floor. The yield strength (V_y) and peak strength (V_p) of the trilinear backbone can be calculated using overstrength factors, which are determined through statistical analyses of extensive experimental or analytical results (Fig.3). The deformation parameters (δ_y, δ_p and δ_u) of the backbone curves are also determined through the statistical analyses of a large number of experimental results. The hysteretic parameter can be determined according to its structural type using the method of previous studies [7][9].

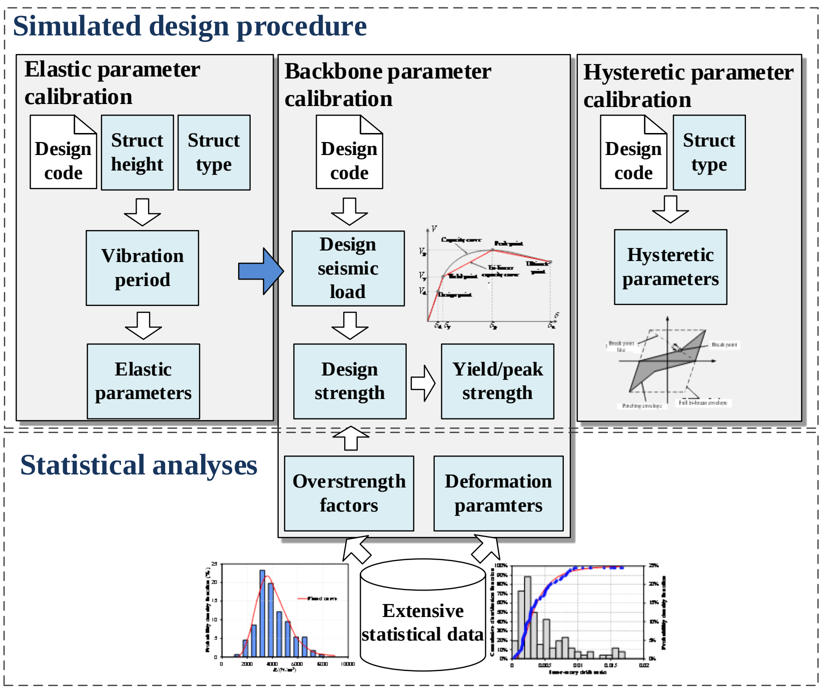


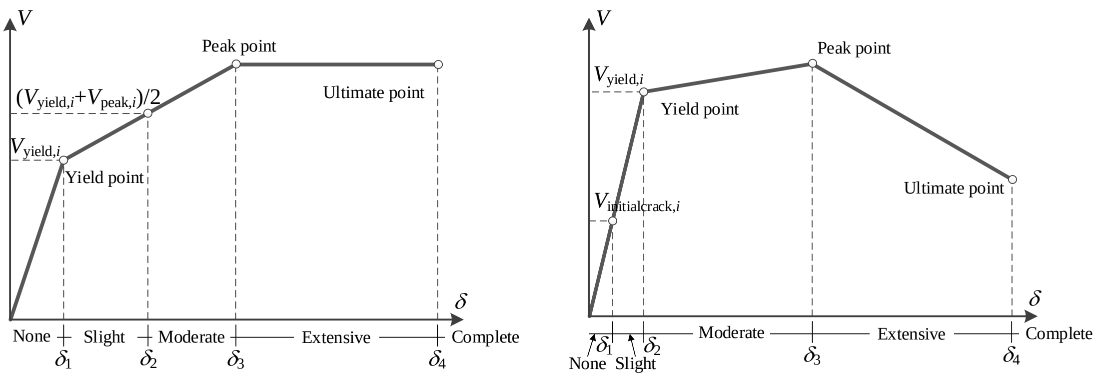
Fig. 3 – Schematic view of the parameter determination method

4. Damage assessment

According to the Hazus report [7] and the Chinese code (i.e., Classification of Earthquake Damage to Buildings and Special Structures [19]), seismic damage to buildings can be classified into five levels (i.e., none, slight, moderate, extensive and complete damages). To assess the seismic damages of buildings, there are two sets of criteria in existing literatures: (1) the force-based damage criteria [20] and (2) the deformation-based criteria [16]. The force-based criteria define the damage states according to the inter-story shear force. In contrast, the deformation-based criteria define the damage states according to the inter-story deformation.

Both the force-based damage criteria and the deformation-based damage criteria have their advantages and limitations. At the earlier stage of seismic damage, the stiffness of a structure is high, and a small variation in deformation will lead to a significant change in the internal force; thus, the force-based damage criteria are more reliable. In contrast, when approaching the peak strength, the tangent stiffness of a structure is quite small, and a small variation in force will induce a significant deformation change; thus, the deformation-based damage criteria are more suitable.

This study defines the damage states by taking the advantages of both the force-based and deformation-based damage criteria. The force-based damage criteria are used for the "slight" and "moderate" damage states, whereas the deformation-based criteria are used for the "extensive" and "complete" damage states, as shown in Fig.4.



(a) RC frames (b) Masonry structures

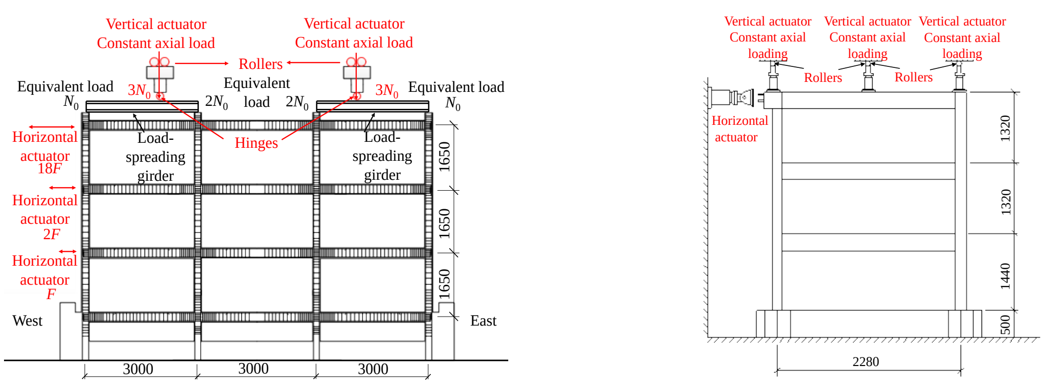
Fig. 4 – Inter-story backbone curves and damage limits

5. Validation

The pseudo-static tests of three individual buildings are used to validate the proposed parameter determination method and damage assessment method.

5.1 Validation for RC frames

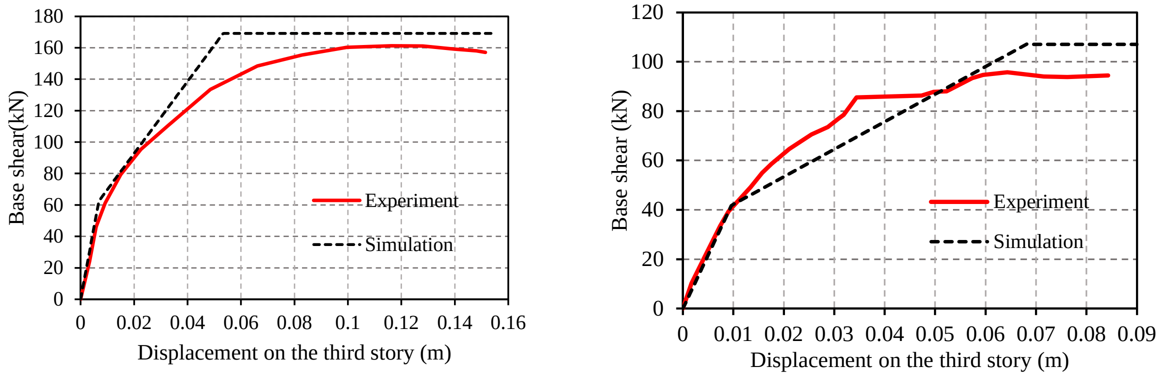
Two experiments of RC frames [21, 22] are used to validate the proposed method. Both of the two frames are designed according to Chinese codes [23, 24]. Frame 1 is a 1:2 scale test while Frame 2 is a 1:2.5 scale test. The experiment is shown in Fig.5a and Fig.5b.



(a) Frame 1 (b) Frame 2

Fig. 5 – Test setup of the RC frames (unit: mm)

The capacity curves of the simulation and the experimental results are compared in Fig.6. Both simulations show good agreement, which demonstrates that the proposed parameter determination method can estimate the backbone curves of RC frames reasonably well.

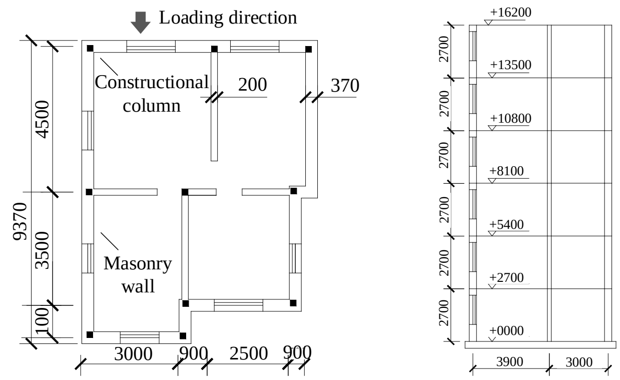


(a) Frame 1 (b) Frame 2

Fig. 6 – Capacity curves of the RC frames

5.2 Validation for a RM structure

Wang et al. [25] have performed a full-scale, pseudo-static test of an RM structure. The layout of the masonry structure is shown in Fig.7. The predicted results and the test results are compared in Fig.8, and the two curves have a good agreement, which demonstrates the reliability of the parameter determination method for the RM structure.



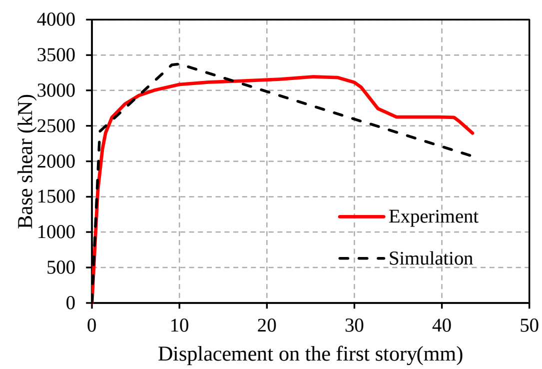


Fig. 7 – Layout of the RM structure (unit: mm)

Fig. 8 – Comparison for the RM structure

6. Regional seismic damage prediction for Longtoushan Town

THA-based regional seismic damage prediction is used to estimate the seismic damages of Longtoushan Town during 2014 Ludian earthquake. The conventional damage probability matrix method is also applied to compare with the proposed method.

6.1 Comparison with field investigation results

The post-earthquake field investigation of Longtoushan Town has collected the attribute data and damage information of 56 buildings. The buildings are simulated with the MCS models in Fig.2a and the parameters of each building are determined using the method proposed in Section 3.

The ground motions recorded in Longtoushan Town are shown in Fig.9. Because the peak ground acceleration (PGA) of this earthquake attenuated quickly [13], the ground motions recorded at 16 different stations are collected, and the fitted attenuation relationship is shown in Fig.10. The ground motion is scaled according to the distance to the epicenter using the attenuation relationship in Fig.10, and input to each of the 56 buildings.

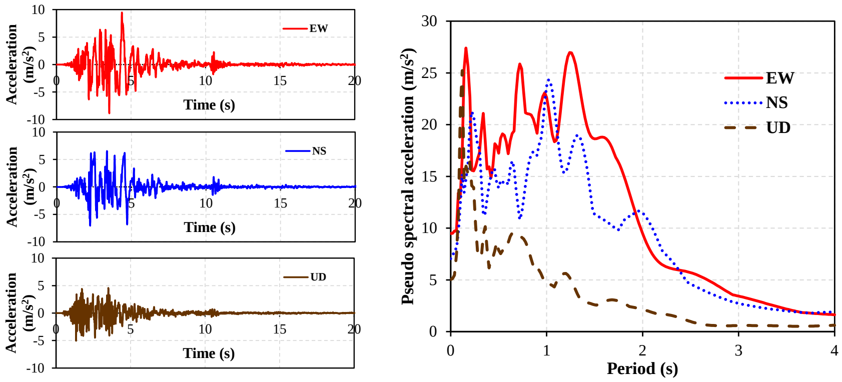


Fig. 9 – Ground motions recorded at Longtoushan Town station

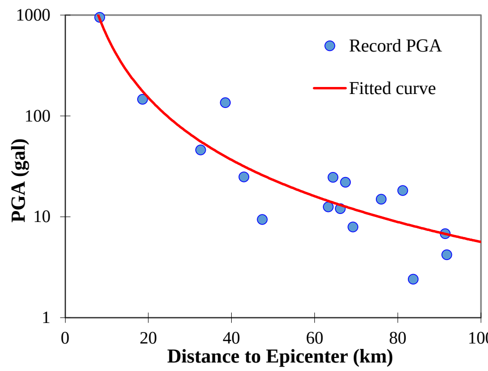


Fig. 10 – The attenuation function of Ludian earthquake

The simulated damage states are compared with the damage states obtained from the field investigation, as shown in Fig.11. The comparison indicates that for half of the buildings in Longtoushan Town, the simulated damage states are identical to those of the field investigation. The differences in the remaining damage states are within one damage state level. Given the complexity of the actual situation of buildings and the variation of ground motions, the result shown in Fig.11 is deemed to be acceptable. The proposed method can predict the regional seismic damage with reasonable accuracy and reliability.

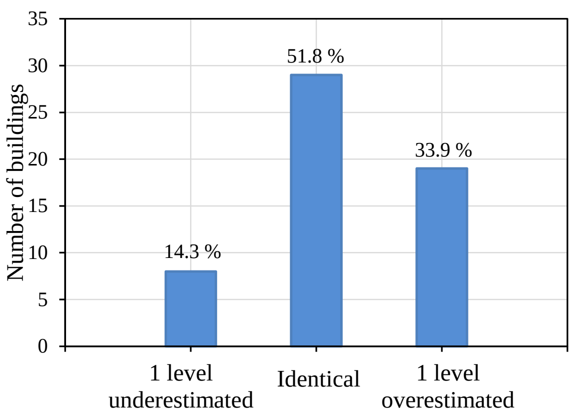


Fig. 11 – The comparison between the predicted damage states and actual damage states

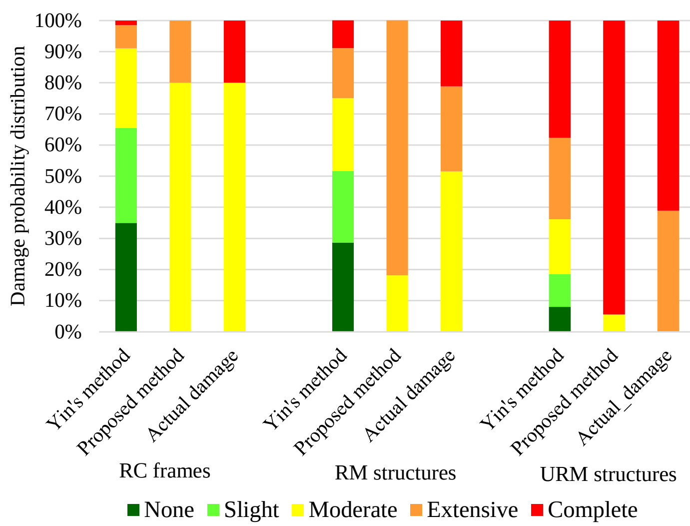


Fig. 12 – Comparison of predicted seismic damage and actual damage

6.2 Comparison with damage probability matrix method

Yin [26] proposed the damage probability matrices of different types of buildings based on the building damage data of several large earthquakes in China, which have been widely used [27]. Therefore, the damage probability matrices of Yin are used, and the prediction is compared with that of the proposed method.

According to the data from the China Earthquake Administration [28], the modified Mercalli intensity of the Ludian earthquake is Level IX in Longtoushan Town. The seismic design intensity of buildings in this region is VII. Therefore, the damage probability matrices of Classes A, B and C with seismic design intensity VII proposed by Yin are adopted for the RC frames, RM structures and URM structures in Longtoushan Town, respectively [26]. The seismic damage predicted by the damage probability matrix method and the proposed method are compared in Fig.12. Fig.12 shows that Yin's damage probability matrix method significantly underestimates the damage to Longtoushan Town, because the ground motion recoded in Longtoushan Town was proven to be destructive despite the relatively low magnitude (M6.5) of the Ludian earthquake [13].

Therefore, the THA-based regional seismic damage prediction can more accurately consider the effects of local ground motions and building conditions and yields more reasonable results.

7. Conclusions

The THA-based regional seismic damage prediction method for multi-story buildings is proposed in this work. The method is validated using the pseudo-static tests of three individual buildings, which demonstrates the accuracy and reliability of the method. Finally, the proposed THA-based regional seismic damage prediction method is used to estimate the seismic damages of Longtoushan Town after the 2014 Ludian earthquake, which is proved to be more accurate than the results obtained by the damage probability matrix method.

8. Acknowledgements

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