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Application of the FEMA P-58 Methodology to Predict Earthquake Loss of a Region Area

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Abstract

Earthquake-induced building collapses have been effectively mitigated in recent years. However, earthquake-induced economic losses have continued to rise. Following the objective and procedure of next-generation performance-based seismic design, the economic loss prediction method proposed by FEMA P-58 (referred to as “the FEMA P-58 method” hereafter) is introduced for regional earthquake loss prediction in this study. The engineering demand parameters (EDPs) for a large number of buildings within a region are efficiently obtained through nonlinear time history analysis (THA) using multi-story concentrated-mass shear (MCS) models. The building data, including structural and nonstructural components, is obtained through field investigation, structural and architectural drawings, and default database published from the FEMA P-58 document. The proposed FEMA P-58 method is implemented for a region located in China to demonstrate the implementation and advantage of using the FEMA P-58 method for regional earthquake loss prediction. The results show that the probability of complete loss due to collapse is relatively low. But the loss associated with significant repair and irreparable damage is very high. In addition to the advancement in loss simulation for a region, the proposed methodology can also be used to identify the loss distribution within a building. The result can also be used to study the influence of the different ground motion characteristic on the regional loss.

Keywords: earthquake engineering, FEMA P-58, earthquake economic loss, regional seismic damage simulation

1. Introduction

Earthquakes are one of the most destructive natural disasters, especially when they occur in an urban area with dense population and high volume of infrastructures. The seismic resistance of buildings has been improved significantly over the last 3 decades. Earthquake induced building collapses on new constructions have been effectively controlled. By contrast, the economic loss due to earthquake is still very high. For example, during the 2010 M8.8 Maule earthquake in Chile, only 4 buildings constructed after 1985 were collapsed [1]. This shows the building code is very effective. But this earthquake still caused a direct economic loss of US$ 30.9 billion which represents 24% of the global economic damages from all natural disasters in 2010 [2]. Hence, it is crucial to develop a robust earthquake loss prediction model for an urban area, where the information can be used by the decision makers to make informed risk management decisions.

HAZUS [3] is one of the most widely used methods for regional earthquake loss prediction [4]. HAZUS calculates the building response using capacity spectrum method (CSM) [5], in which buildings are treated as a single-degree-of-freedom (SDOF) system and subjected to a pushover analysis. There are three major limitations when using HAZUS to predict regional earthquake loss: (1) The financial loss between different stories cannot be differentiate as the simulation model is based on SDOF model; (2) The financial loss for the nonstructural components cannot be characterized well as the classification is rather general. (3) The influence of the ground motion characteristics (e.g. near-field velocity pulses) on the building damage and economic loss cannot be easily considered using the CSM [6].

A solution for the above limitations of the HAZUS method is provided by the FEMA P-58 report "Seismic Performance Assessment of Buildings, Methodology and Implementation", which is referred to as "the FEMA P-58 method" hereafter [7, 8]. The fragility curve of every structural and nonstructural components in a building is directly considered in the FEMA P-58 method during the seismic assessment. The FEMA P-58 method has been successfully applied to many individual buildings [9, 10, 11, 12]. However, currently there is no such application for regional predictions. The primary challenge when using the FEMA P-58 method for regional earthquake loss predictions is the difficulty of obtaining detailed seismic responses (i.e., engineering demand parameters, or EDPs) and collecting the structural and nonstructural component data for every building in the region.

To address this limitation, a practical approach for regional earthquake loss prediction based on the FEMA P-58 method is proposed in this study. This approach allows detailed prediction of the economic loss at each story of each building in a region. To obtain the EDPs of each building, a series of multi-story concentrated-mass shear (MCS) models were developed and used in the nonlinear time history analyses (THA). The building data and the structural and nonstructural component information were obtained through field investigation and design drawings. The values of the fragility curves were adopted from FEMA P-58 study. One building in the Tsinghua University campus located in Beijing, China was chosen as the demonstration building for the detailed implementation of the proposed earthquake loss assessment of a region. Finally, an intensity-based earthquake loss prediction model of the entire Tsinghua University (including 619 buildings) was performed. The outcomes of this work can be used as a reference for future earthquake loss prediction model for large urban areas

2. Loss Prediction Methodology

The fundamental principle of the FEMA P-58 loss assessment methodology is the performance-based earthquake engineering framework proposed by the Pacific Earthquake Engineering Research Center [13, 14, 15]. Three loss prediction methodologies have been proposed in FEMA P-58 document [7]. In this study, the intensity-based assessment method is adopted.

Fig.1 shows the flowchart of applying the FEMA P-58 method for an urban area. The process consists of three parts: 1) assemble the building performance model; 2) analyze the building response to determine EDPs; and 3) calculate the economic loss.

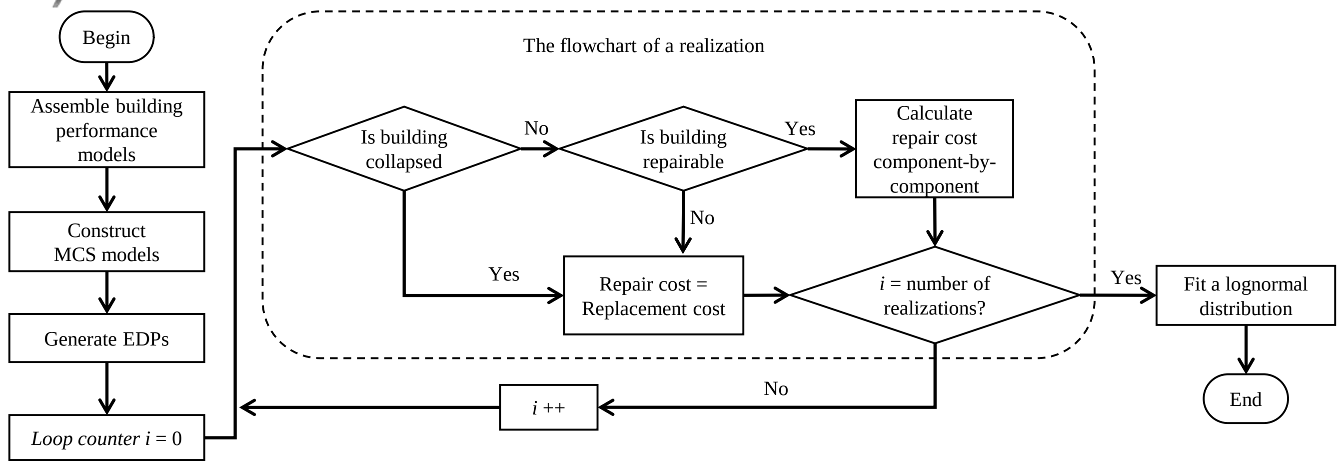


Fig. 1 – Flowchart of the FEMA P-58 methodology for building earthquake loss prediction

The key challenges of using the FEMA P-58 method to a region are: (1) the assembly of performance models, (2) rapid calculation of EDPs, and (3) prediction of the collapse fragility of a building group. Fig.2 shows the recommended procedure.

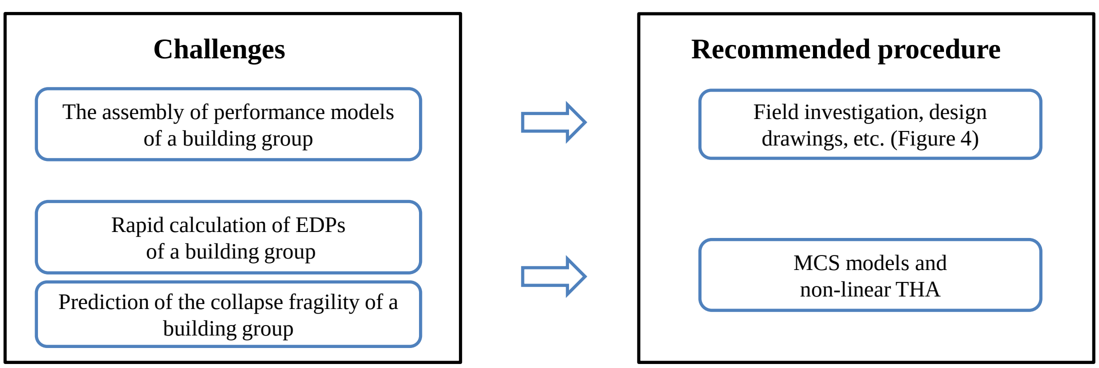


Fig. 2 – Challenges and recommended procedure of extending the FEMA P-58 method to a region

(1) Assembly of the performance models

The performance model of buildings contains the basic information with both the structural and nonstructural performance groups (PGs). The information can be collected through the procedure as shown in Fig.3. The basic building data can be obtained from a geographic information system (GIS) database, field investigation, or design drawings. Generally, such information is easy to collect if a GIS database of the target area is available.

Assemble building performance models	
Basic building data	• GIS，investigation，design drawings，other information
Structural PGs	• Method A: according to building design drawings • Method B: according to design drawings of neighborhood buildings with similar building data • Method C: making estimation according to field investigation
Nonstructural PGs	• Buildings of major occupancies (e.g. classroom, resident, office, etc.): obtaining distribution of PGs by investigation • Other buildings: according to normative quantity information provided by FEMA P-58

Fig. 3 – Approach to assembling the performance models of a building group

If the exact replacement value of the building is missing, the replacement value of the building can be determined by summing the average repair cost of each PG at its most severe damage state.

Three recommended procedures have been proposed to determine the structural PGs.

(a) Method A: If the structural and architectural drawings of the building are available, the type and quantity of each PG can be obtained from these drawings directly. Once the PG information has been identified, the repair cost for the PG can be defined using the fragility data published by the FEMA P-58 document.

(b) Method B: If structural and architectural drawings of the target building are not available, but there is a similar building (with similar year of construction, structural type and occupancy) in the neighborhood, the quantity of the structural PGs of the target building can be estimated according to those of the neighborhood buildings with actual structural and architectural data.

(c) Method C: For buildings where neither the design information nor similar building information is available, the PG information can be estimated according to the field investigation of the buildings.

To determine the nonstructural PGs information, the buildings are categorized into groups according to building occupancies. In each group of occupancy (e.g. office buildings), the distribution of the nonstructural PGs can be identified from a detailed site visit of several typical buildings. Other PGs which are difficult to estimate (such as pipelines) can be identified according to the normative quantity information provided by Appendix F of FEMA P-58 [7]. For other specialized buildings, the nonstructural PGs can be estimated according to Appendix F of FEMA P-58 [7].

(2) Rapid calculation of the EDPs of a building group.

Another difficulty in extending the FEMA P-58 method from an individual building to a region is to obtain the EDP distribution in an efficient manner. The MCS models proposed by Lu et al. [6] were adopted in this study. MCS model is a common numerical model to simulate the nonlinear response of multiple-story buildings. MCS model assumes that:

(a) A multiple story building can be simplified to a multiple degree-of-freedom (MDOF) model, where each story has its nonlinearity;

(b) The nonlinear response of the building is assumed to be dominated by the shear mode;

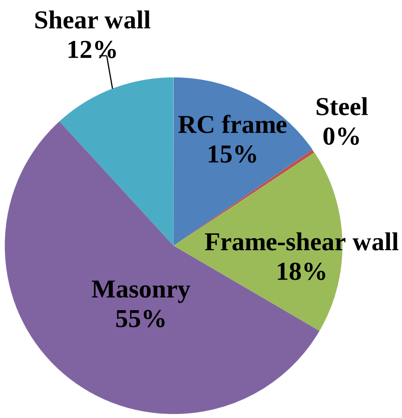
(c) Depending on the structural system, the nonlinearity of the structure at each story can be modeled using either modified-clough, bilinear elasto-plastic or pinching model.

(3) Prediction of the collapse fragility of a building group.

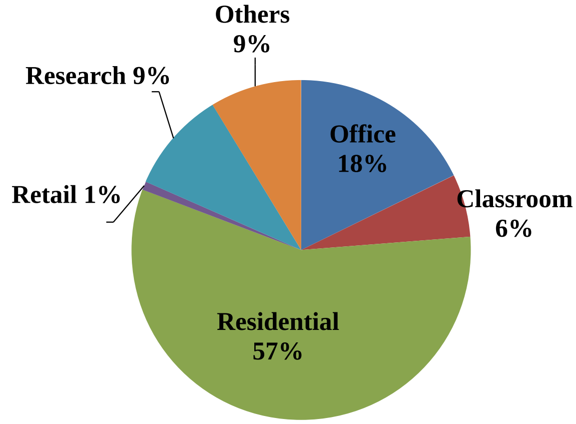
As indicated in the FEMA P-58 methodology, the collapse fragility curves of buildings are needed for the loss calculation. The response analysis of buildings adopted in this work based on the MCS model and non-linear THA can estimate whether a building will collapse when subjected to a particular ground motion [16]. Thus, the collapse fragility curves can be obtained directly by conducting an incremental dynamic analysis (IDA) using the proposed MCS model for each building.

3. Case Study

A case study of Tsinghua University campus with a gross area of approximately 4 km^2, consisting of 619 buildings, is performed. According to the Chinese Code for Seismic Design of Buildings [17] and corresponding geological investigation, the buildings in Tsinghua University shall be designed for seismic design intensity of VIII which represents a peak ground acceleration (PGA) of 0.2 g at the 10% probability of exceedance in 50 years hazard level. The site condition is classified as class II in Chinese code, which corresponds to site class C and D as presented in the ASCE 7-10 [18, 19]. Fig.4 shows the percentage of different structural types and building occupancies. It can be seen that masonry structures has the highest percentage. A large amount of structures are residential.



(a) Percentages of different structural types



(b) Percentages of building occupancies

Fig. 4 – Composition of buildings in Tsinghua University

In this work, 50 pairs of the horizontal components of the ground motion records for site classes C and D proposed by FEMA P695 [20] are adopted. According to the Chinese Code for Seismic Design of Buildings [17], PGA is selected to quantify the shaking intensity.

Three earthquake shaking intensities namely the service level earthquake (SLE) (with a PGA of 0.07g and return period of 50 years), design basis earthquake (DBE) (with a PGA of 0.2g and return period of 475 years), and maximum considered earthquake (MCE) (with a PGA of 0.4g and return period of 2475 years) were included.

4. Results and Discussion

4.1 Validations

Due to the lack of credible regional seismic loss study in the target area, the loss results in this study are not able to be compared with other studies. Instead, the earthquake loss results of typical buildings are compared with those calculated using "Performance Assessment Calculation Tool (PACT)" (an earthquake loss simulation software developed by FEMA to implement FEMA P-58 method [7]) for validation.

Fig.5 shows the comparison of the earthquake loss of a 4-story RC frame office building (named RC_Office). The result was normalized based on the building replacement value. Each curve in Fig.5 consists of 1000 Monte Carlo simulation results. As shown in this figure, the loss simulation results presented between these 2 approaches are very similar.

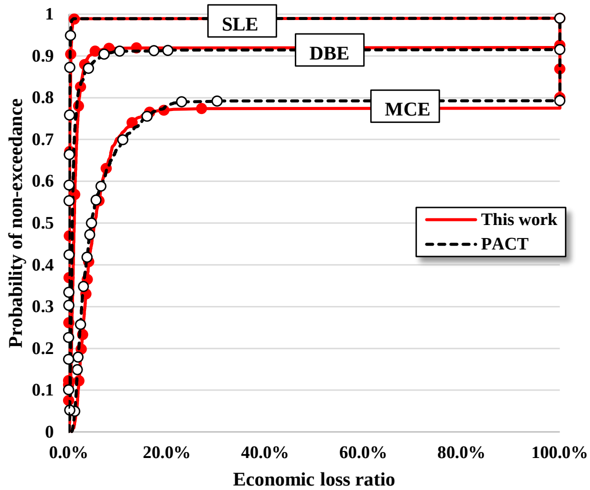
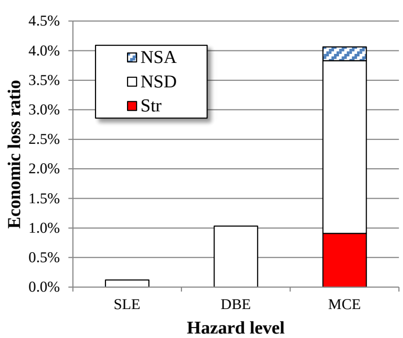


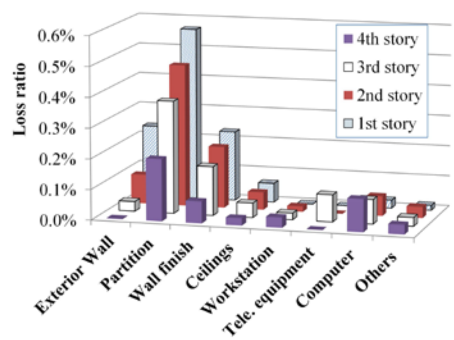
Fig. 5 – Comparison of the loss results of RC_Office predicted by the proposed method and by PACT

4.2 Earthquake loss prediction of an example building

Fig.6 (a) shows the sample results of the loss simulation of the RC_Office. At the SLE, the RC_Office building remain nearly elastic and suffers no structural damage. However, there are some damages related to the drift-sensitive nonstructural (NSD) PGs. The repair cost mainly contributed from the partitions and the wall finishes. When the intensity reaches the DBE, the loss associated with the structural and acceleration-sensitive nonstructural (NSA) PGs increases. The method can also be used to examine the breakdown of the losses. Fig.6 (b) shows the detailed breakdown of the loss associate with the nonstructural PGs at each story of the RC_Office building at the MCE shaking. The result shows that a high percentage of the repair costs come from nonstructural walls (including exterior walls, partitions, and wall finishes).



(a) Loss result



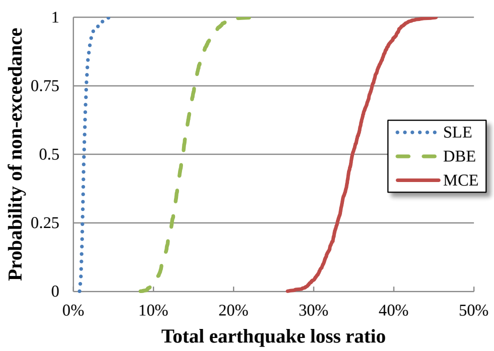
(b) The loss details of nonstructural PGs at each story of RC_Office at the MCE level

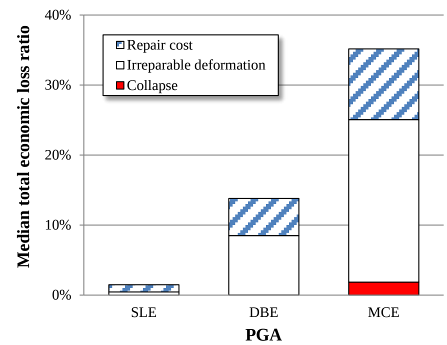
Fig. 6 – Earthquake loss prediction results of RC_Office

4.3 Earthquake loss prediction of the entire campus

Fig.7 (a) shows the earthquake loss prediction of the entire Tsinghua campus under three levels of earthquake shaking intensities. The total earthquake loss ratio is defined as the ratio of total earthquake loss to the total replacement value (US$ 7.476 billion). The median total loss ratio is 1.3%, 13.7% and 34.9% for the SLE, DBE and MCE hazard level, respectively. The median loss is further classified into the losses due to building collapse, irreparable deformation, and repair cost. Fig.7 (b) shows the distribution of the median repair cost. At the SLE hazard level, the economy loss is mainly concentrated from repair costs. When the earthquake intensity increases, the loss starts to contribute from both repair costs and irreparable deformation. As the shaking intensity reaches the MCE hazard level, the contribution from the collapse-induced loss is introduced but the percentage is very low (less than 2%), which is similar to the loss results observed in the 2010 Chile earthquake [1] and 2011 Christchurch earthquake [23].

In addition to the loss assessment from the 50 pairs of ground motions, a side study about the influence of the ground motion velocity pulse on the building performance and earthquake loss is also studied. The results from the loss simulation were compared between the 14 pairs of near-field records with pulse and the other 14 pairs without pulse. Fig.8 shows the economic loss increases when the region is subjected to pulse type motion. This shows the proposed approach is able to quantify the influence of the ground motion characteristics, such as velocity pulse, on building earthquake response and loss prediction. By contrast, according to [24], the HAZUS method cannot identify the influence of the ground motion.





(a) Cumulative probability of total earthquake loss ratio (b) Distribution of the total earthquake loss ratio

Fig. 7 – Loss results of the entire campus under the three hazard levels

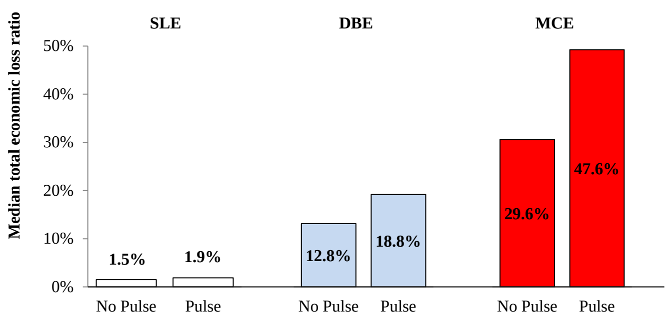


Fig. 8 – The influence of velocity pulse on economic loss of case study region detected by the proposed method

5. Conclusions

(1) MCS models can be used to calculate the structural response for each building at each story with high efficiency, which solves one of the key challenges to extend FEMA P-58 method from an individual building to a region.

(2) For the case study, when the shaking intensity reaches the SLE hazard level, the total earthquake loss mainly contributes from the repair costs. On the other hand, when the hazard level increases to the MCE, the total earthquake loss mainly contributes from the repair cost and the cost of the demolition and reconstruction of irreparable buildings. The percentage of loss caused by building collapse is low.

(3) The proposed approach can be used to study the influence of ground motion characteristics, such as velocity pulse, on building earthquake response and loss, which improves the HAZUS method.

6. Acknowledgements

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7. Copyrights

8. References

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