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BUILDING SEISMIC LOSS PREDICTION BASED ON BIM AND FEMA P-58

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Abstract

Predicting the seismic loss of a building is critical for its resilience. The next-generation performance-based design code released by the Federal Emergency Management Agency, i.e., FEMA P-58, provides a systematic methodology for seismic loss predictions. FEMA P-58 contains the prediction methods and sufficient loss data of structural and nonstructural components, and has been widely used in seismic loss predictions. In FEMA P-58, the performance group (PG) that is a group of components classified by their seismic performances, is regarded as the basic unit for the predictions of seismic damage and loss. The components in a PG share a fragility curve and a consequence function. Specifically, the fragility curves can provide the probabilities of different seismic damage states (DSs) according to the engineering demand parameters (EDPs), while the consequence functions contain unit loss data corresponding to different DSs and are used for predicting the seismic losses of PGs.

However, some limitations exist for the PGs of FEMA P-58 on the acquisition and visualization of loss data. For data acquisition, defining the unit loss data of PGs for different regions require significant statistic work, which limits the application of FEMA P-58 in different regions. Specifically, the original consequence functions of FEMA P-58 were determined based on the data of building costs in Northern California in 2011. If such functions are used in other regions, these consequence functions must be adjusted according to the local building costs. Otherwise, they will lead to large deviations. For example, the investigation of the L'Aquila earthquake in Italy indicates that the predicted seismic loss using FEMA P-58 has an error range of 30–48% compared with the actual loss. Regarding visualization, the spatial distribution of the predicted seismic damage and loss cannot be displayed directly, because the prediction results using FEMA P-58 are only related to the PGs and are not connected to specific components. However, components with the same DS may have different repair strategies owing to their different spatial locations. Therefore, the clear visualization of the spatial distributions of seismic damage and loss is critical for deciding repair strategies.

This study proposes a prediction method of seismic losses combining the BIM and FEMA P-58. First, a component-level damage prediction algorithm is designed to establish the mapping from the BIM components to the PGs, and predict the component damage using the BIM-based time-history analysis (THA) and the fragility curves of the PGs. Subsequently, an ontology-based model considering the deduction rules in the local unit-repair-cost database is created for obtaining exact measurement data of component in a BIM. Meanwhile, a component-level loss prediction algorithm is developed using the measurement data and the unit repair costs corresponding to DSs, by which the predicted seismic losses can agree with the actual situation of the specific region. Finally, a component-level visualization algorithm is designed to display the seismic damage and loss in a virtual reality (VR) environment. A six-story office building in Beijing is used as a pilot test to demonstrate the advantages of the proposed method. The outcome of this study produces a component-level and visual loss prediction result that agrees with the actual situation of the specific region, which can be used to evaluate the post-earthquake economic resilience of different buildings.

Key words: Seismic loss; BIM; FEMA P-58; component level; ontology

1. Introduction

When subjected to an earthquake, some buildings may avoid collapse but still be demolished owing to their high repair costs[1][2]. For example, over 60% of buildings were demolished in the central business district of Christchurch, New Zealand, after an M6.2 earthquake on Feb 22, 2011 [3], which cannot satisfy the resilience demand. Predicting the potential seismic loss of a building is critical for its resilience.

The next-generation performance-based design code released by the Federal Emergency Management Agency[4][5], i.e., “Seismic performance assessment of buildings” (FEMA P-58), provides a systematic methodology for seismic loss predictions. FEMA P-58 contains the prediction methods and sufficient loss data of structural and nonstructural components, and has been widely used in seismic loss predictions [6][8]. In FEMA P-58, the performance group (PG) that is a group of components classified by their seismic performances, is regarded as the basic unit for the predictions of seismic damage and loss. The components in a PG share a fragility curve and a consequence function. Specifically, the fragility curves can provide the probabilities of different seismic damage states (DSs) according to the engineering demand parameters (EDPs), such as inter-story drift ratios (IDRs) and peak floor accelerations (PFAs), while the consequence functions contain unit loss data corresponding to different DSs and are used for predicting the seismic losses of PGs. The seismic loss of a building can be calculated by integrating the data of all PGs.

However, some limitations exist for the PGs of FEMA P-58 on the acquisition and visualization of loss data. For data acquisition, defining the unit loss data of PGs for different regions require significant statistic work, which limits the application of FEMA P-58 in different regions. Specifically, the original consequence functions of FEMA P-58 were determined based on the data of building costs in Northern California in 2011 [4]. If such functions are used in other regions, these consequence functions must be adjusted according to the local building costs. Otherwise, they will lead to large deviations. Regarding visualization, the spatial distribution of the predicted seismic damage and loss cannot be displayed directly, because the prediction results using FEMA P-58 are only related to the PGs and are not connected to specific components. However, components with the same DS may have different repair strategies owing to their different spatial locations. Therefore, the clear visualization of the spatial distributions of seismic damage and loss is critical for deciding repair strategies.

This study proposes a prediction method of seismic losses combining the building information model (BIM) and FEMA P-58 [9]. First, a component-level damage prediction algorithm is designed to establish the mapping from the BIM components to the PGs, and predict the component damage using the BIM-based time-history analysis (THA) and the fragility curves of the PGs. Subsequently, an ontology-based model considering the deduction rules in the local unit-repair-cost database is created for obtaining exact measurement data of component in a BIM. Meanwhile, a component-level loss prediction algorithm is developed using the measurement data and the unit repair costs corresponding to DSs, by which the predicted seismic losses can agree with the actual situation of the specific region. Finally, a component-level visualization algorithm is designed to display the seismic damage and loss in a virtual reality (VR) environment. A six-story office building in Beijing is used as a case study to demonstrate the advantages of the proposed method. The outcome of this study produces a component-level and visual loss prediction result that agrees with the actual situation of the specific region, which can be used to evaluate the post-earthquake economic resilience of different buildings.

2. Framework

The framework of the proposed seismic loss prediction method based on BIM and FEMA P-58 is shown in Fig. 1. It includes three steps: damage prediction, loss prediction, and result visualization.

Step 1: The damage prediction aims at predicting the seismic damage of each component using BIM and FEMA P-58. The FEMA P-58 method can only be used to predict the damage of PGs; therefore, the mapping relationships from the components in the BIM to the PGs in FEMA P-58 are first established in this step. Subsequently, the THA based on the BIM is performed to obtain the EDPs, which avoids the manual modeling workload of structural models. Subsequently, the damage of PGs can be calculated using the fragility curves in FEMA P-58. Finally, the damage of PGs is mapped back to the components in the BIM. Thus, the DS of each component can be obtained.

Step 2: The loss prediction is used to predict the seismic loss of each component using the BIM and the unit-repair-cost database. First, an ontology-based model is created to extract the exact measurement data of the components considering the deduction rules in the local unit-repair-cost database from a BIM. Subsequently, the unit repair costs corresponding to different DSs of the components are calculated based on the unit-repair-cost database and the FEMA P-58 method. Finally, the losses of different components and the entire building can be calculated, separately.

Step 3: The visualization is designed to display the spatial distribution of the component damage and loss using BIM technology. First, a unified standard for the visualization of damage and loss is established. Subsequently, a visualization algorithm of damage and loss is developed to meet the multiple requirements of observation. Finally, a VR program is developed to allow users to observe the detailed information and spatial distribution of damage and loss in a virtual walkthrough.

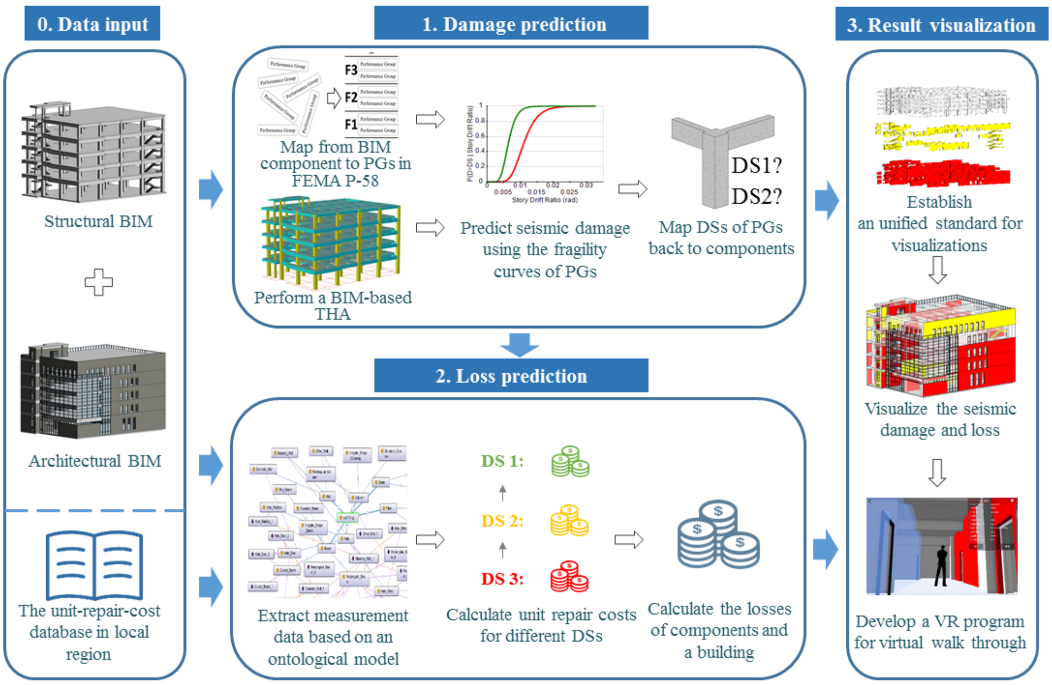


Fig. 1. Framework of this study [9]

3. Technical implementation

3.1 Seismic damage prediction based on BIM and FEMA P-58

The seismic damage prediction for the components includes four steps: (1) establish the mapping relationships between the components in the BIM to the PGs in FEMA P-58; (2) convert the BIM into a structural analysis model and perform THA for predicting the EDPs and structural deformations; (3) predict the damage of the PGs based on the EDPs in step (2) and the fragility curves in FEMA P-58; (4) reversely map the damage of the PGs to the components and obtain the DSs of the components. The details of these four steps are illustrated below.

Step 1: Mapping from components to PGs

In FEMA P-58, each PG has a unique ID and a detailed classification criterion. The mapping from a component to the PG is to determine the corresponding PG's ID for each component according to its classification criterion. The classification of the PGs in FEMA P-58 considers the geometries, materials, constructions, and damage mechanisms. Generally, the geometrical and material properties can be obtained from the BIM; however, the information of construction and damage mechanism must be added manually. Therefore, a solution combining the automatic and manual procedure is adopted to establish the mapping relationships from the components to the PGs herein.

Step 2: THA based on BIM

Converting a BIM into a structural analysis model can reduce the workload in modeling. Several structural analysis programs contain such a conversion function, such as ETABS [10], Robot [11], and YJK[12]. In this study, YJK is selected as the structural analysis program. This is because numerous structural sub-models for the joints and sections in Revit have been developed in YJK [13], resulting in high conversion efficiency from a BIM to a structural analysis model.

Using the YJK plug-in in Revit, the structural components that will be converted to the structural analysis model are selected. These selected components will be matched to the sections and joints (e.g., columns and beams) with the predefined sub-models in YJK. Finally, these sub-models are exported in the format of a .ydb file. In YJK, the structural model is first created by importing the .ydb file. Subsequently, the structural loads such as gravity are assigned to the model, and the corresponding ground motion is selected for a nonlinear THA. Finally, the EDPs (e.g., IDRs and PFAs) and structural deformations (e.g., plastic-hinge rotations) produced by the THA are output for the following damage prediction of components.

Step 3: Seismic damage prediction of PGs

Through the fragility curves, the probabilities of a PG at different DSs can be determined under a given EDP.

Step 4: Reverse mapping of DSs from PGs to components

Even though the components belong to the same PG on the same story, they may exhibit different DSs. For example, in a PG of masonry walls on a certain story, the probabilities of DS1, DS2, and no damage predicted by FEMA P-58 are 22%, 28%, and 50%, respectively, when the corresponding peak IDR is 0.002. However, FEMA P-58 does not provide the DS of each component. Hence, a reverse mapping algorithm of DSs from PGs to components is designed to determine the DS of each component.

The mapping principles of nonstructural and structural components are different. For nonstructural components, the distribution of DSs on the same story exhibits a large uncertainty [14-15]. Therefore, DSs can be randomly assigned to the components belonging to the same PG. For structural components, the distribution of DSs should be consistent with the results of the THA. The rotations of plastic hinges calculated by the THA are adopted as an indicator to map the DSs to the joints of structural components (e.g., beams, slabs, and columns).

3.2 Loss prediction based on BIM and the unit-repair-cost database

(1) Ontology-based acquisitions for the measurement data of components

In the unit-repair-cost database, there are plenty of deduction rules for measuring components. For instance, the volume of a wall should subtract the holes of the windows and doors on this wall. To calculate such deductions automatically, an ontology-based model is created following these deduction rules strictly.

The creation of an ontology-based model includes two important steps [9]: (a) establish ontological relationships of components; (b) define semantic reasoning rules for the deductions between components.

(2) Acquisitions of unit repair costs

Many governments and professional associations have published the official construction codes, such as the MasterFormat code [16-17], and the Beijing repair code [18]. By using the unit-repair-cost database in these codes, the loss prediction result will agree with the actual situations in the local area. However, these cost data only correspond to the state of complete damage. The consequence functions in FEMA P-58 provide the unit repair costs corresponding to different DSs. Therefore, the ratio of costs between different DSs in FEMA P-58 can be used to calculate the unit repair costs corresponding to different DSs in the database.

In this study, the function F(*P58_ID*, *DSn*) was established. This function will obtain the unit repair cost of a component with a *P58_ID* at *DSn* from the consequence functions in FEMA P-58. Define the unit repair cost of a component in the database as *Unit_Cost_Max*. If this component is a nonstructural component, the unit repair cost corresponding to *DSn*, denoted as *Unit_Cost_DSn*, can be calculated by Equation (1):

$$Unit\_Cost\_DSn = \frac{Unit\_Cost\_Max * F(P58\_ID, DSn)}{F(P58\_ID, DS\_Max)} \tag{1}$$

where, *P58_ID* is the ID of the corresponding PG of this component, and *DS_Max* represents the maximum DS of the PG.

If the component is a structural component, it has more than one P58_IDs. Thus, the average of the repair costs for the joints is used to calculate its repair cost. The unit repair cost of a structural component corresponding to *DSn* is as shown in Equation (2):

$$Unit\_Cost\_DSn = \frac{Unit\_Cost\_Max * \sum_i^J F(P58\_ID_i, DSn)}{\sum_i^J F(P58\_ID_i, DS\_Max)} \tag{2}$$

where J means the number of joints connected to this component, and $P58\_ID_i$ is an ID of the PG of the joints.

(3) Loss predictions

Assume the DS of component i is *DSn*, and the corresponding measurement data is V_i, the repair cost of this component, $Repair\_Cost_i$, can be calculated by Equation (3):

$$Repair\_Cost_i = Unit\_Cost\_DSn_i \times V_i \tag{3}$$

where $Unit\_Cost\_DSn_i$ is the corresponding unit repair cost of the component.

Repair_Cost, which is the repair cost of the entire building, can be calculated by Equation (4):

$$Repair\_Cost = \sum_{i=1}^N Repair\_Cost_i \tag{4}$$

where N represents the total number of components in this building.

3.3 Visualization of seismic damage and loss

(1) A unified visualization standard

According to FEMA P-58, the numbers of DSs of the components are different. For example, the joints of beams and columns generally contain three DSs, while masonry walls generally contain two DSs. To visualize the DSs of the components in a unified manner, two different visualization modes are designed in this study: the absolute mode and the relative mode.

In the absolute mode, each DS is marked with a certain color. The absolute mode can display the DSs of a component directly; however, it is difficult to demonstrate whether the components can be repaired. For example, a beam-column joint at DS2 can be repaired, while a masonry wall at DS2 will be generally dismantled. Therefore, in this study, a relative mode is established to demonstrate the reparability of the components. Specifically, DSs are classified as repairable and irreparable. Hence, only three states need to be presented, using three colors.

The losses of different components vary significantly. Therefore, a relative mode is used. The losses are divided into four categories based on the ratio of repair cost and construction cost.

(2) 3D Visualization and virtual walk through

Fuzor [19] is used as the VR platform in this study, because it can load a BIM into the VR scene with sufficient information corresponding to the components. Through the "Fuzor Plugin" in Revit, the colored BIM is synchronized to the VR scene for a walk through. During the walk through, not only the distribution of the DSs or losses can be observed by the colored components, but also the value of loss of each component can be checked in the VR scene of Fuzor, which benefits the decision making of repair strategies.

4. Case study

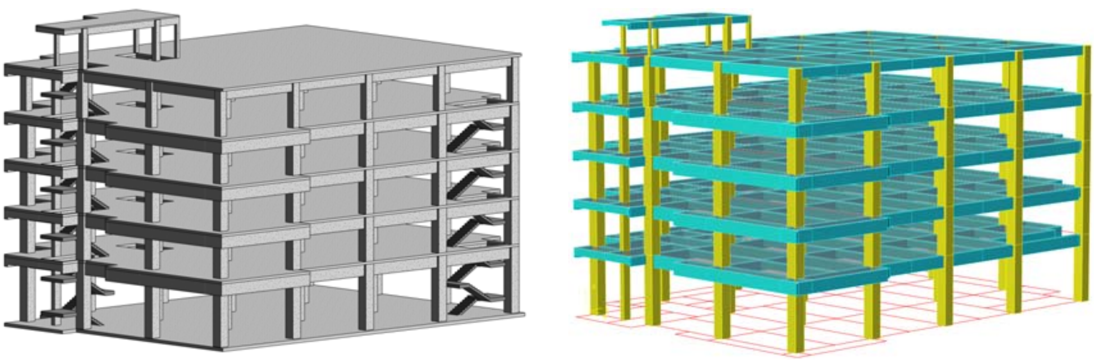
4.1 Introduction of a case study

An office building in Beijing is selected for a case study. It is a reinforced concrete (RC) frame building with a length of 33.6 m and a width of 25.2 m. The building encompasses 921 m2 and has six stories with a total height of 25.5 m. The BIM of this building is established in Revit, as shown in Fig. 2.

Fig. 2.The BIM of the case study [9]

4.2 Seismic damage prediction

Using the YJK plug-in in Revit, the structural model in the BIM is converted into a structural analysis model in YJK directly, as shown in Fig. 3. Hence, the workload of modeling can be eliminated.



(a) Structural model in a BIM (b) Structural analysis model in YJK

Fig. 3.The structural analysis model created by a BIM [9]

According to the seismic design code [20], the peak ground acceleration (PGA) for the maximum considered earthquake is 400 cm/s2 in Beijing. Therefore, the widely used El-Centro ground motion with a

PGA of 400 cm/s2 is selected as the input in both the *X*- and *Y*- directions of the structure. Nonlinear THA is performed in YJK, and the EDPs required by the following predictions are calculated.

The proposed methods of seismic damage and loss prediction, and the visualization are developed as the Revit plug-in. After reading the EDPs above, the DSs and losses of all the components are predicted using the developed plug-in and written to the attribute tables of the components.

Fig. 4 shows the results of the seismic damage prediction. Only 1% of the beam-column joints exhibit repairable damage, while the remainders are intact. The reinforced masonry walls exhibit severe damages. In detail, 51% and 16% of them exhibit irreparable and repairable damages, respectively. Further, 70% of the stairs are damaged but repairable. Owing to the slight damage in the structural components, the entire building is slightly damaged.

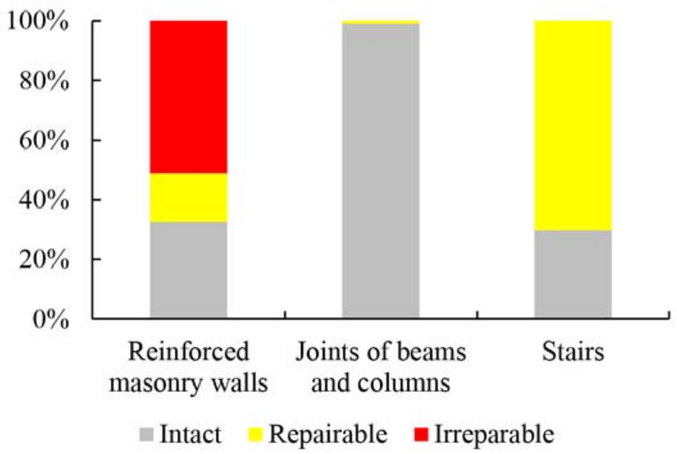


Fig. 4.The results of the seismic damage prediction [9]

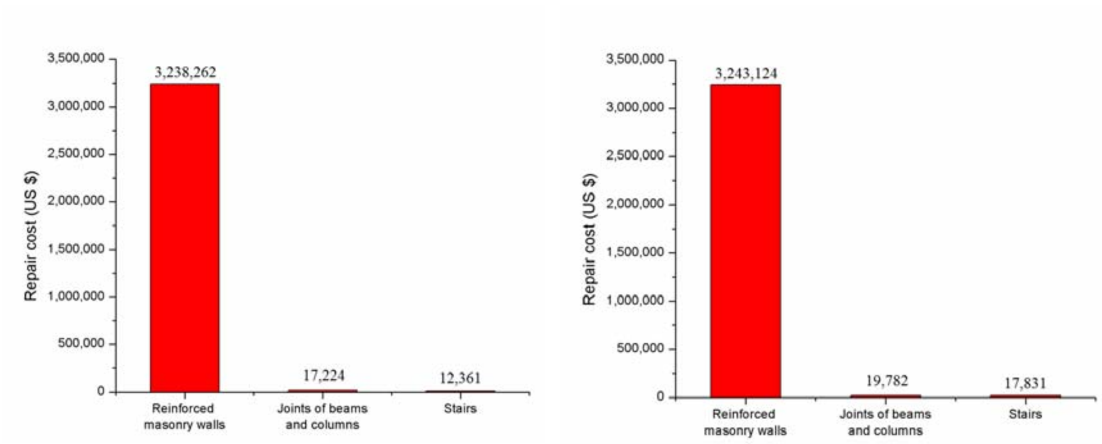
4.3 Seismic loss predictions and comparisons

To compare the FEMA P-58 method and the proposed method, three scenarios are considered, as shown in Table 1. The differences between these three scenarios are the prediction methods and the unit-repair-cost database.

Table 1 Prediction scenarios

Scenario	**Prediction method**	**Unit-repair-cost database**
1	FEMA P-58	Database in FEMA P-58
2	The proposed method	Database in FEMA P-58
3	The proposed method	Database in Beijing repair code

Through the proposed method, the seismic losses of different components and the entire building in three scenarios can be predicted. Fig. 5 shows the distributions of the repair costs in scenario 1 (using the FEMA P-58 method and the U.S. repair cost data), and scenario 2 (using the method proposed in this study and the U.S. repair cost data). This figure shows that the repair costs of different components predicted by these two methods are almost the same. The total repair costs in scenarios 1 and 2 are $3,267,847 and $3,280,737, respectively. From the comparison, when using the same unit-repair-cost database, the prediction of the proposed method is almost the same as the FEMA P-58 method, which indicates the accuracy of the proposed method.



(a) Scenario 1 (b) Scenario 2

Fig. 5.Distributions of repair costs in scenarios 1 and 2 [9]

Fig. 6 shows the distribution of the repair costs in scenario 3 (using the proposed method and the Chinese repair cost data). As shown, the loss distribution among different components is consistent with that of scenario 2. However, the total repair cost predicted in scenario 3 is much lower than that of scenario 2. The total repair cost of scenario 3 is 463,728 RMB (the U.S. $70,003 according to the exchange rate [21-22] between RMB and U.S. dollar in 2011), which is only 2% of the total repair cost ($3,267,847) of scenario 1.

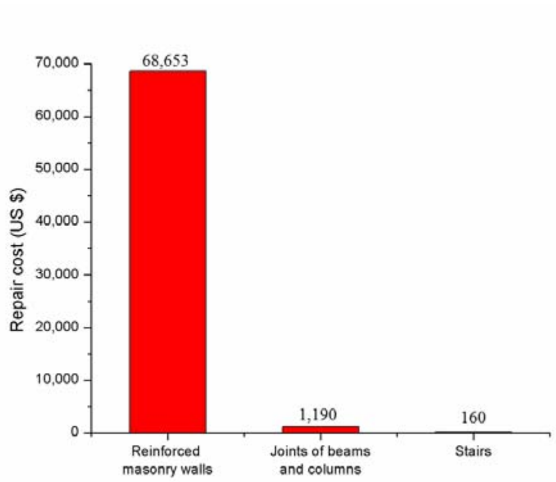


Fig. 6.Distributions of repair costs in scenario 3 [9]

Reinforced masonry walls constitute the largest proportion of losses in all scenarios. In the database of FEMA P-58, the unit repair cost of the reinforced masonry wall in this case study is $15,800/225 ft2, while the corresponding data in the Chinese database is only $334/225 ft2. A significant difference of 47 times exists between these two databases. Therefore, such significant differences result in a significantly different loss prediction.

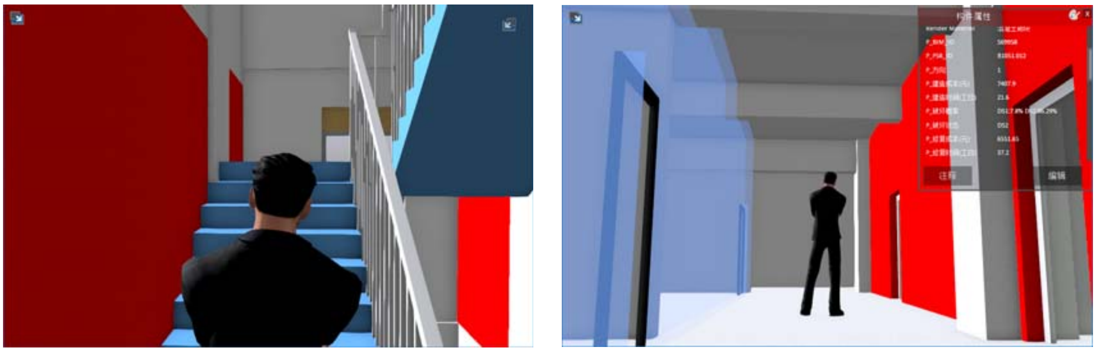
According to the investigations from several earthquakes that occurred in China, the ratio between the loss and construction cost for an RC structure with slight damage is 5–10% [23]. The average construction cost in 2011 in Beijing is $227/m2 [24]; therefore, the total construction cost of this building is $1,204,235. Through the calculations, the ratio between the loss and construction cost is 5.8% in scenario 3, which agrees with the empirical result (5–10%), while the ratio in scenario 2 is 272.4%, which is much larger than the empirical range. Therefore, the proposed method of earthquake loss predictions agrees much better with the actual investigations in China.

In addition, the proposed methods including the predictions of seismic damage and loss as well as the corresponding visualizations are integrated with BIM, which can be implemented in an efficient and nearly-automatic way; whereas the FEMA P-58 method cannot directly use the detailed data in a BIM, leading to a lot of manual work for obtaining the required data of predictions. On the other hand, the FEMA P-58 method has no visualization function, which limits its application effects. The advantages of the visualization function in the proposed method are clarified as follows.

4.4Visualization

According to the ratios between the repair cost and construction cost, the earthquake losses of all the components are shown in Fig. 7. Additionally, the colored BIM in Fig. 7 is loaded in Fuzor. The virtual walk through inside the building is performed (see Fig. 8), so that the distribution of losses inside the building can be clearly observed and the detailed information about the seismic damage and loss of the selected component can be obtained. The virtual walk through can help users to fully understand the spatial distribution of seismic damage and losses, so that a reasonable repair strategy can be crafted.

Fig. 7.Visualization of seismic losses of components [9]



(a) Seismic losses inside the building (b) Loss information for a selected component

Fig. 8.Virtual walk through inside the building [9]

5. Conclusions

(1) By integrating FEMA P-58 with BIM, the proposed method mapped the seismic damage results of PGs in FEMA P-58 to specific components in BIM, and could save the manual works (e.g., the structural modeling for THAs and the data collections for determining the PG's ID in FEMA P-58).

(2) In the seismic loss predictions, the proposed method exhibited the same accuracy as the FEMA P-58 method when using the same database. Moreover, the loss predictions through the proposed method were in agreement with the actual investigations in different regions when using the local database.

(3) The proposed method was able to display the spatial distribution of seismic damage and losses of all the components in a virtual walk-through way, which helps users make a specific repair strategy considering the loss distributions.

(4) The outcome of this study produced a component-level and visual loss prediction result that agrees with the actual situation of the specific region, which can be used to evaluate the post-earthquake economic resilience of different buildings.

Acknowledgments

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