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COLLAPSE SEISMIC RISK ASSESSMENT FOR IRREGULAR MID-RISE BUILDINGS

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Mid-rise buildings, which may be used as office or apartment buildings, are very common structures in urban areas. Because these buildings are usually heavily populated, the casualty caused by the collapse of these structures in an earthquake could not be overestimated. Therefore, developing a suitable assessment method to identify these buildings with high collapse risk is an important issue. This paper presents a probabilistic assessment method, which involves nonlinear response-history analysis together with incremental dynamic analysis (IDA), to assess the collapse risk of a mid-rise building, so high-risk buildings and their damage patterns can be identified. This methodology is developed based on the procedure of collapse fragility analysis proposed by FEMA P-58, while the local and damage global criteria that define collapse failure are adopted from ASCE 41-13 and PEER-TBI, respectively. Finally, for demonstration, the proposed procedure is applied to assess the collapse risk of a mid-rise RC building that collapsed in a major earthquake occurred in Taiwan, 2016.

Keywords: Fragility analysis, Nonlinear response-history analysis, Incremental dynamic analysis, Probabilistic method.

1 INTRODUCTION

The goal of traditional seismic design methods for buildings is to ensure life safety under the given design earthquake level; therefore, the seismic performance of the structure under different earthquake levels cannot be evaluated, nor quantified using a traditional design approach. To assure that a newly-designed or a retrofitted existing building is able to meet the owner's seismic demand, the approaches using the concept of performance-based earthquake engineering (PBEE) for seismic design and evaluation were advocated in recent decades (FEMA P-58 2018, Alhamaydeh *et al*. 2013). On the other hand, in urban areas, mid-rise (MR) buildings are very common structural systems. Since these buildings are usually heavily populated, the casualty and social impact caused by the collapse of these structures in an earthquake can not be overestimated. Therefore, developing a suitable assessment method to identify the buildings with high collapse risk becomes a critical issue. Nevertheless, most of collapse assessment methods for building commonly used by professional engineers are static push-over methods, which may be suitable for low-rise buildings but may not be able to accurately predict nonlinear seismic behavior of a taller or irregular building structure under an extreme earthquake. Based on the probabilistic framework of FEMA P-58 (2018), this paper aims to propose a methodology and a practical produce to quantify the collapse prevention (CP) capacity of a MR building, so that MR buildings with high collapse risk can be screened out and the weakening elements of the buildings that may cause the collapse can be identified. This procedure is developed based on the method of collapse fragility analysis suggested by FEMA P-58, while the local and global criteria that define collapse failure are adopted from ASCE 41-13 (2013) and PEER-TBI (2010), respectively, and the performance index and its acceptance criterion is adopted from FEMA P-695 (2009). This procedure contains several operational steps that can be easily followed by professional engineers.

2 PROPOSED PROCEDURE FOR COLLAPSE ASSESSMENT OF BUILDINGS

Figure 1 shows that the proposed procedure for the probabilistic collapse assessment of a building structure. The procedure involves 7 operational steps that are explained step by step below by using an example structure. For detail description, please refer to the article by Hsieh *et al*. (2018).

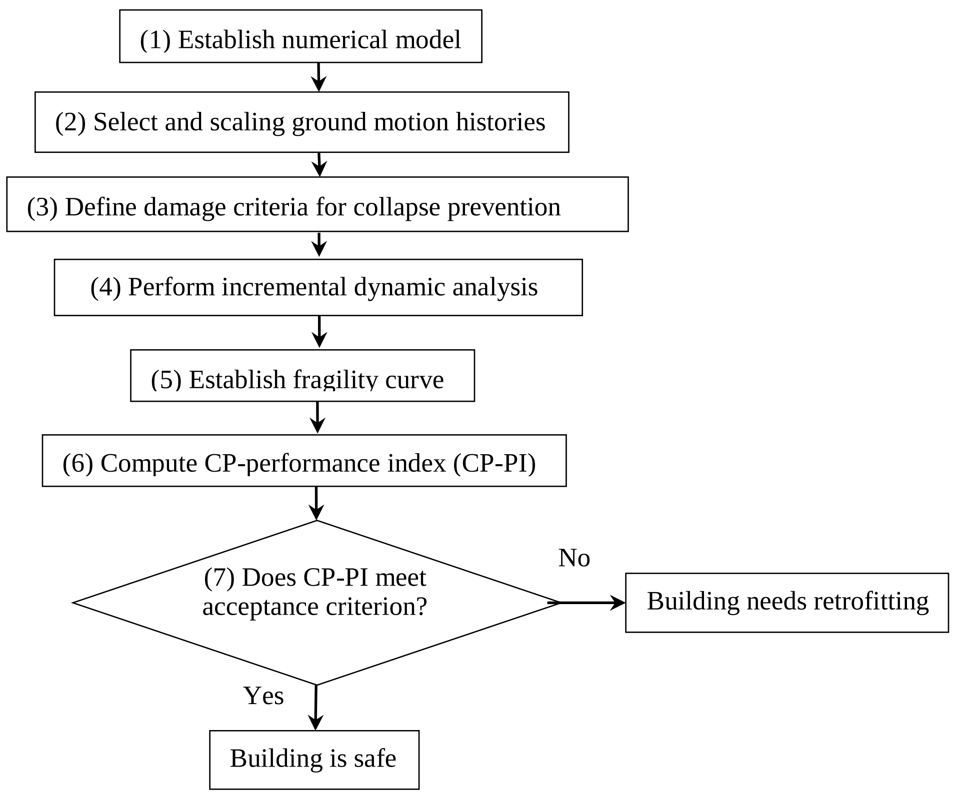

Figure 1. Flowchart of proposed procedure for building collapse assessment method.

2.1 Step 1 – Establish Numerical Model for The Structure to Be Assessed

In this study, a mid-rise building that collapsed during the Meinong Earthquake on Feb. 6, 2016 will be used as an example. Using this example, the step-by-step evaluation process of proposed collapse assessment method will be illustrated. This example building was a reinforced concrete building located in Yong-Kang District, Tainan, Taiwan. It was 16-storey building above ground level. The elevation view of the numerical model for this building is shown in Figure 2. The fundamental periods of this building are 2.12s and 1.67s along the shorter and longer sides, respectively, so the average fundamental period is $\bar{T} = 1.89$ s. In the model, nonlinear plastic hinges were assigned to the two ends of each column.

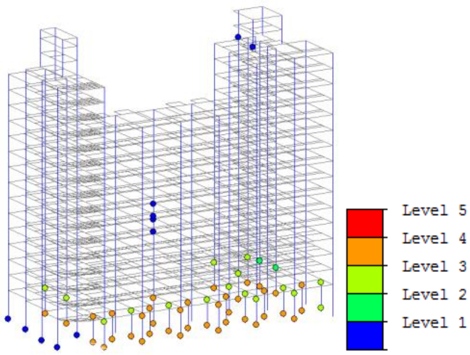

Figure 2. Example building with different levels of plastic hinges.

Table 1. Damage criteria for CP performance level.

Damage criteria	Description
Local criterion	Plastic hinge of any column reaches its ductility limit μ_b defined by ASCE 41-13.
Global criterion	The maximum story drift of any story reaches $\theta_{max} \geq 4\%$

2.2 Step 2 - Selection and Scaling of Ground Motions

FEMA P-58 (2018) recommends that when performing nonlinear dynamic analysis, the influence of horizontal bi-directional ground motions on structural response has to be considered. Therefore, 11 pairs of bi-directional ground motions have to be pre-selected from data base, and used as the input ground motions in the IDA that follows. The geometric-mean response spectra of these 11 pairs of bi-directional ground motions have to be consistent with the shape of the pre-determined target response spectrum. In this study, for convenience, the design spectrum specified in the local design code was selected as the target spectrum.

2.3 Step 3 - Define Collapse Criterion

Since building collapse can be caused by failure of some local components or instability of the overall structure on the verge of collapse, in this study, two types of collapse criteria (see Table 1), namely, the local and the global failure criteria are considered for the example building. (1) Global failure criterion: According to PEER-TBI (2010), most of flexible structural systems begin to decay significantly between the maximum story drift of 3%-5%. In this condition, the structural system is very likely to collapse since it is severely degraded. Since the example building may be classified as a flexible structural system, based on the above observation, the maximum story drift of 4% is considered as the global CP failure criterion in this study. (2) Local failure criterion: The occurrence of structural collapse may be also caused by the failure of some local components, particularly columns, due to the degradation of either element strength or stiffness, which gradually leads to the instability of the overall structural system. Therefore, in addition to the global failure criterion, in this study, the element failure criterion based on the ductility definition of ASCE 41-13 (2013) is also employed for each individual column. As shown in Table 1, the local failure criterion is defined as when any one of column components (vertical load-carrying components) reaches its ductility limit μ_b and loses its load-carrying capacity. A typical force-deformation relation for the plastic hinge of a structural component is shown in Figure 3. The ductility capacity μ_b for the structural component is defined as in Eq. (1);

$$\mu_b = 1 + (b / \theta_y) \tag{1}$$

where parameter b is the limit drift angle as shown in Figure 3, θ_y is the drift angle of the components when yielding occurs, which will be automatically computed in most of commercial structural analysis software.

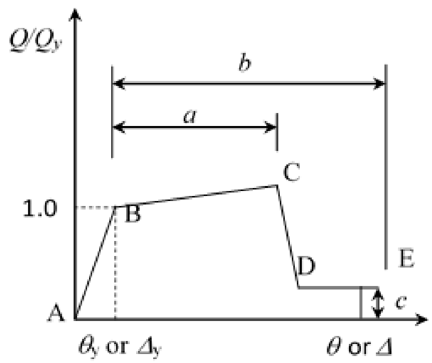

Figure 3. Typical force-displacement relation for a plastic hinge (ASCE 41-13).

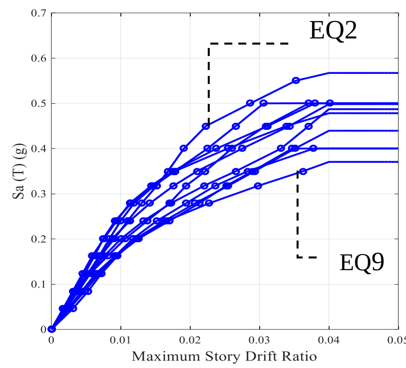

Figure 4. IDA curve of example building.

2.4 Step 4 - Perform Incremental Dynamic Analysis (IDA)

With failure criteria defined in step 3, the incremental dynamic analysis can be conducted on the established numerical model of the building. In the IDA, by using the geometric-mean spectral acceleration $S_{gm}(\overline{T})$ (where $\overline{T}$ is the average fundamental period of the building) as the intensity measure, the intensities of the 11 pairs of ground motions are gradually increased, and then nonlinear dynamic analysis for the evaluated building is performed for each ground motion with gradually increased intensity. The result of IDA is shown graphically in Figure 4. The horizontal and vertical axes of Figure 4 are the maximum inter-story drift $\theta_{\max}$ and the seismic intensity $S_a(\overline{T})$, respectively. Each curve in the figure represents the inter-story drift due to a specific ground motion with sequentially increased intensity. Whenever the local or the global collapse criteria (see Table 1) is reached for a ground motion at a particular intensity, the building is considered to be at the verge of collapse. The process of IDA can be stopped until more than half or all of the ground motions reach either one of the collapse criteria of the building. In this study, the process of IDA proceeded till all ground motions reach the collapse criteria.

2.5 Step 5 - Establish Collapse Fragility Curve (CFC)

The collapse fragility curve can be established using the result of the IDA. A collapse fragility curve, which can be described mathematically as $P(Collapse \mid S_a(\overline{T}) = x)$, represents the collapse probability at a given ground motion intensity of $S_a(\overline{T}) = x$. Figure 5 shows the CFC of the building shown in Figure 2. The vertical and horizontal axes of Figure 5 represent the collapse probability and the ground motion intensity $S_a(\overline{T})$, respectively. The CFC, which is usually developed using the statistic model of log-normal distribution, can be determined by two statistic parameters, namely, the median $\hat{S}_a(\overline{T})$ and logarithmic standard deviation β. In Figure 5, the small circles represent the data points obtained from the IDA, while the broken line represents a regression fragility curve whose median $\hat{S}_a(\overline{T})$ and logarithmic standard deviation β (also called dispersion) were obtained from the regression of the IDA data points by the method of most likelihood. The median $\hat{S}_a(\overline{T})$ in the CFC represents the ground motion intensity at which half of the selected ground motions will cause building collapse. The value of the dispersion β obtained from the IDA result (i.e., the dispersion of the broken line) is discard and is replaced by more practical values suggested by the charts of FEMA P-58 (2018), which are able to reflect uncertainties associated with quality of construction, reliability of mathematical model and response variation due to different ground motions, etc. In Figure 5, the solid line whose median and the dispersion are taken to be $\hat{S}_a(\bar{T}) = 0.429g$ and $\beta = 0.5723$, respectively, represents the CFC of the example building with FEMA P-58 suggested dispersion value of $\beta = 0.5723$. This curve will be used for the later collapse assessment of the building.

2.6 Step 6 - Determine CP-Performance Index

In this study, the performance index (PI) for collapse prevention is defined as the collapse probability P_{MCE} under the MCE-level earthquake, which can be expressed as in Eq. (2);

$$PI = P_{MCE} = P(Collapse \mid S_a(\bar{T}) = S_a(\bar{T})_{MCE}) \tag{2}$$

where $S_a(\bar{T})_{MCE}$ represents seismic intensity at the MCE level (also, the spectral acceleration at the period of $\bar{T}$ for the MCE), which is usually specified in a seismic design code. Once $S_a(\bar{T})_{MCE}$ is given, the value of P_{MCE} can be readily determined from the collapse fragility curve as shown in Figure 5. For example, the building shown in Figure 2 has an average fundamental period of $\bar{T} = 1.89$s, and according to the Taiwanese seismic code, the MCE spectral acceleration at 1.89s is about 0.40g, i.e., $S_a(\bar{T})_{MCE} = 0.40$g. From Figure 5, the collapse probability for $S_a(\bar{T}) = 0.40$g is $P_{MCE} = 45\%$. This probability value is summarized in Table 2.

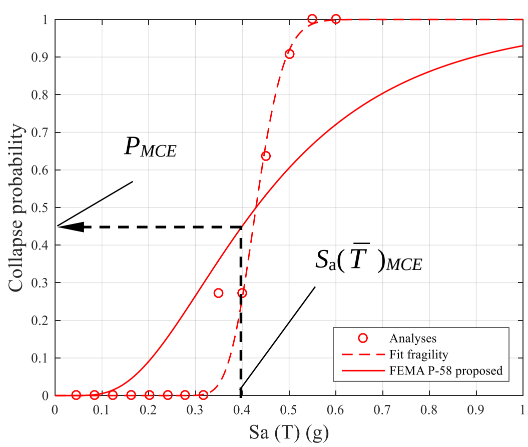

Figure 5. Collapse fragility curve of the example building.

Table 2. Result of collapse assessment of the example building.

Example building	Collapse probability under MCE
CP-Performance index	$P_{MCE} = 45\%$
Acceptable level	$P_{MCE} \leq 10\%$

2.7 Step 7 – Check PI with Acceptable Level

In order to screen out buildings with high collapse risk and to determine whether seismic retrofitting is needed for the assessed building, the acceptable level for the computed *PI* has to be quantified. In this study, the acceptable performance level is defined using the acceptable collapse probability for MCE recommended by FEMA P-695 (2009) and ASCE 7-16 (2016). According to Section 7.1.2 of FEMA P-695 (2009), the acceptable collapse probability under the

MCE-level earthquake is equal or less than 10%. As determined in Step 6 (see Figure 5), the collapse probability for an MCE earthquake is $P_{MCE} = 45\%$, which is much higher than the acceptable level of 10% as summarized in Table 2. Therefore, it is concluded that the example building does not have sufficient collapse prevention capacity and needs seismic retrofitting.

3 CONCLUSIONS

When subjected to an extreme earthquake loading, the nonlinear dynamic behavior of a mid-rise (MR) building can be very complicated, particularly for those MR buildings with structural irregularity. Therefore, the collapse prevention (CP) capacity of these buildings evaluated by conventional push-over seismic assessment methods may not be conservative. To overcome this deficiency, this study proposes a probabilistic assessment method, which involves nonlinear increment dynamic analysis, suitable for evaluating the CP performance of a MR building. The proposed procedure that contains 7 operational steps can be easily implemented by professional engineers. The procedure was developed based on the probabilistic procedure of collapse fragility analysis suggested by FEMA P-58, while the collapse damage criteria were adopted from ASCE 41-13 and PEER-TBI reports. Furthermore, in order to screen-out buildings with high risk of collapse, in this study, the CP performance index is defined as the collapse probability under the MCE-level earthquake, while the acceptable performance level was adopted from FEMA P695, which suggested that the acceptable collapse probability under the MCE must be less than 10%. Finally, the proposed assessment method was demonstrated by using an example MR building that collapsed in a major earthquake in Taiwan. The performance index computed according to the proposed method indicates that the example building had collapse risk much higher than the recommended acceptable level, and should have been retrofitted before the earthquake occurred. The applicability of the proposed method is checked against one example only, more examples may have to be checked before it can be generalized.

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