Advanced Materials Research Vols. 133-134 (2010) pp 1259-1264

doi:10.4028/www.scientific.net/AMR.133-134.1259

Performance-Based Seismic Evaluation of Historical Buildings

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Abstract In this paper, limit state criteria for safety evaluation of historical buildings according to different target period of usage were introduced briefly. The effect of beam-column connection and the contribution of bricks surrounded columns and infill masonry walls on the seismic behavior of the historical buildings were identified based on calculation results. Main features of performance-based seismic evaluation method, including classification of importance of historical buildings, determination of target period of usage and performance index, were discussed. An engineering project was discussed to illustrate the evaluation procedures, and verify the effectiveness of the evaluation method.

Keywords: Historical building, performance-based, seismic evaluation, target period of usage, pushover analysis

Introduction

Historical buildings are significant cultural heritages and special concerns should be paid on the protection and the retrofitting of those outstanding buildings. There was virtually no earthquake fortification included in the original design of historical buildings. Besides, human activities and environmental factors have caused severe damages to those buildings. As a result, seismic damages of the historical buildings will be more serious than the buildings constructed in modern ages. Consequently, seismic behavior evaluation of historical buildings is a key problem for the protection of these buildings.

The bearing capacity principle in current design codes for new buildings was usually adopted while assessing seismic behavior of historical buildings. According to the evaluation results, lots of retrofit measures needed to be adopted to meet the requirement of earthquake fortification in most cases. There is a contradiction between conservation and excessive strengthening of historical buildings. First, for historical buildings their performance is measurable and the target period of usage is not equal to the design reference period used for new structures, therefore the reliability evaluation of existing buildings is different from the design of new buildings; secondly, interaction between structural members and nonstructural members should be considered, the performance-based seismic evaluation method can also be used to relieve the contradiction between conservation and strengthening. A historical building was analyzed in this study with consideration of the effect of beam-column joint rigidity, contribution of bricks surrounding the columns and the infill masonry walls. The performance-based seismic evaluation method for assessing the seismic behavior of historical buildings was introduced.

Reliability Evaluation of Existing Buildings

For existing buildings, the dead load is constant; the structural parameters can be obtained by in situ inspection. However, most calculation equations of bearing capacity were developed for new buildings, in which the randomness of both the material and the construction quality was considered. Those equations should be modified to be suitable for the assessment of historical buildings. According to the reliability theory and the features of existing buildings, the partial coefficients of the load effect and the resistance can be calculated in such a way (Gu et al. 2004): the partial coefficient for the dead load is adjusted to 1.0 (the value is taken as 0.6 if the dead load is contributing to the structural behavior); the partial coefficient for the live loads is adjusted to 1.3; the partial coefficient for resistances of different members can be obtained according to the optimization analysis and the value is ranged between 1.1 and 1.8. The evaluation results are more reasonable for existing buildings by using the adjusted coefficients. While assessing the reliability of historical buildings, if the ratio of the resistance to the load effect is higher than 0.9, the structural members under this condition should not be strengthened or can only be slightly strengthened if it is necessary.

While assessing the performance of historical buildings, the target period of usage should be determined by the protection level to be achieved for the buildings, current status and requirement of owners, instead of a fixed period, 50 years for example. The live loads varied from different target period of usage have been studied (Gu et al. 2004); fortification intensity for different target period of usage was given according to seismic hazard analysis and the relation between the seismic intensity and the earthquake return period (Sun 2006). The so-obtained fortification intensity was adjusted following the procedure suggested by Gao (1997), based on which the earthquake action can be calculated. The results of the fortification intensity are listed in Table 1.

Table 1: Adjusted fortification intensity (Sun 2006)

Fortification intensity	*6 degree fortification region*					*7 degree fortification region*				
Target period of usage (year)	10	20	30	40	50	10	20	30	40	50
Intensity for evaluation (degree)	5	5	5	6	6	6	6	6	7	7
Fortification intensity	*8 degree fortification region*					*9 degree fortification region*				
Target period of usage (year)	10	20	30	40	50	10	20	30	40	50
Intensity for evaluation (degree)	7	7	7	8	8	8	8	8	9	9

Practical Methods for Seismic Evaluation of Historical Buildings

The evaluation results may be influenced by the rationality of calculation model to a great extent while assessing seismic behavior of historical buildings (Jiang et al. 2005); an engineering example is given to illustrate the practical method for seismic evaluation of historical buildings, which may resolve the contradiction between conservation and excessive strengthening.

The building is located at the bund of Shanghai, built in 1923, and the conservation level belongs to the second class of conservation building, which means the building parts other than the building façade, structural system, plane layout and distinctive decoration is allowed to be retrofitted. The beams of building are all *I* shape, which are encased in concrete; columns are covered with bricks (Fig. 1), they consist of *I* shape formed steel sections and steel plates, which are clinched together. The steel beams are connected to the steel column by steel angle (Fig. 2), thus the structure should be considered as a hinged frame. Provided that the steel beams have perfect connections with the RC slabs, the beam-column joints can be taken as rigid and the structure should be considered as a rigid frame. In fact, the concrete surrounding the steel beams and the RC slab were cast as a whole, and the interaction between RC slab and steel beams turns the structure into a semi-rigid frame; so the analysis should be carried out according to the hinged and rigid model, respectively, while considering the contribution of the surrounded bricks to the column rigidity, and equivalent infill masonry walls into concrete walls. Taking the target period of usage as 50 years and 30 years (the longest period to maintain current function of usage) respectively, and the corresponding fortification intensity are 7 degree and 6 degree, respectively, the calculation results of angular drift between floors of the building under frequent earthquake and natural vibration period are listed in Table 2 and Table 3. The results in the parenthesis are calculated without considering the contribution of the surrounded bricks.

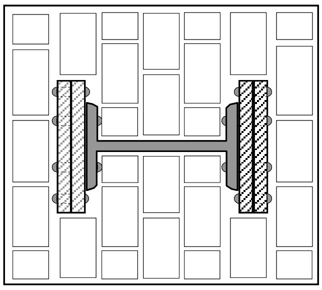

Figure 1: Typical column surrounded with bricks

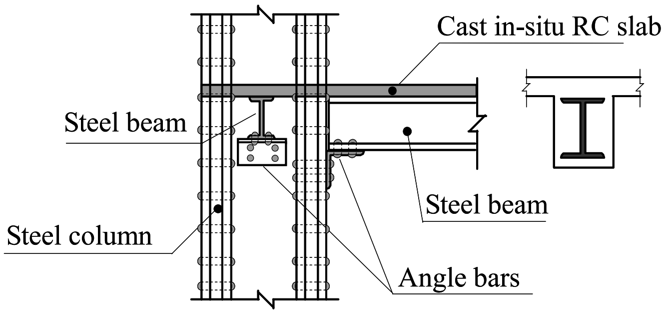

Figure 2: Beam-column joints

From the table, it can be seen that the angular drifts between floors of rigid frame model are much smaller than the hinged frame model, in which the contribution of the infill masonry walls was ignored. Hence the hinged joints should be renovated into rigid ones while retrofitting the historical buildings; the calculation results are also influenced by contribution of the surrounded bricks, so the bricks should be restored properly rather than removed.

The results showed that the system stiffness was increased if the contribution of the infill masonry walls were considered. The resulting natural vibration period is closer to the empirical values; the angular drifts between floors meet the limit value of seismic code. It can then be concluded that the contribution of the infill masonry walls to the integral seismic behavior of structure is relatively important, so proper seismic strengthening measures can be used to strengthen the infill masonry walls.

The seismic behavior of the building can be improved obviously while the contribution of infill masonry walls is considered; however, if the structural deformation caused by the earthquake action is too large, the masonry walls may crack, and the internal force will be redistributed. As a result, the calculation model without considering masonry walls should be used in such case.

Taking 30 years as the target period of usage, the calculation results of the rigid frame model can meet the requirement of current code with considering the contribution of infill masonry walls. It means that the building can meet the needs during the period of 30 years after proper strengthening, which may explain the good status of the building after being used for 80 years.

Table 2: Angular Drift between floors of the building under earthquake

Calculate model		*Fortification intensity*	*Maximum elastic angular drift between floors*	
			Vertical	*Transverse*
With the contribution of masonry walls	Hinged frame model	6 degree	1/5868 (1/5742)	1/2392 (1/2290)
		7 degree	1/2923 (1/2861)	1/1198 (1/1144)
	Rigid frame model	6 degree	1/6331 (1/5827)	1/2697 (1/2473)
		7 degree	1/3165 (1/2913)	1/1349 (1/1236)
Without contribution of masonry walls	Hinged frame model	6 degree	1/208 (1/147)	1/212(1/184)
		7 degree	1/103 (1/73)	1/105 (1/91)
	Rigid frame model	6 degree	1/521 (1/397)	1/645 (1/552)
		7 degree	1//261 (1/199)	1/320 (1/276)

Table 3: Calculation results of natural vibration period

Natural vibration period	Without contribution of masonry wall		With contribution of masonry wall	
	Hinged frame model	Rigid frame model	Hinged frame model	Rigid frame model
T_1 (s)	4.99 (5.94)	2.84 (3.79)	0.851 (0.862)	0.798 (0.831)
T_2 (s)	4.90 (5.39)	2.52 (2.93)	0.622 (0.623)	0.529 (0.549)
T_3 (s)	4.66 (5.18)	2.18 (2.54)	0.594 (0.594)	0.452 (0.478)

Performance-Based Seismic Evaluation of Historical Buildings

Some researchers introduced the principle of performance-based seismic design to the evaluation of historic buildings and indicated a new way for assessing the seismic behavior of historical buildings (FEMA356 2000, Determan and Miyamoto 2006).

The basic concept of performance-based seismic evaluation is to assure that the buildings will achieve expected performance levels under different levels of earthquake action within its target period of usage, and the performance levels are divided into operational(OP), immediate occupancy(IO), life safety(LS) and collapse prevention(CP) in FEMA356. Seismic damage can be evaluated effectively by displacement which is chosen to be the performance index mostly, and the different performance levels correspond to the different displacement limit values (Fig. 3). Seismic evaluation of normal existing buildings is mainly based on the bearing capacity method, but it is more important to control ductility and deformation of the integral structural system for historical buildings. Performance-based seismic evaluation emphasizes the characteristic of the buildings, and appropriate seismic performance objective can be chosen to satisfy the demand of the owners and society. Classification of importance of historical buildings, determination and quantization of performance index are the key combination points.

Seismic fortification criterion is related to the earthquake action and seismic behavior of structures, which is expressed by exceeding probability of earthquake and target period of usage; while assessing the seismic performance of historical buildings, target period of usage is not have to be taken as 50 years. Reversibility is one of the important principles in protecting historical buildings; strengthening measures are not so effective considering the limitation of technical level nowadays, so the possibility for using new technology and material to make conservation work more reasonably in the future should be created. From Table 1, it can be seen that the fortification intensity reduces 1 degree while the target period of usage taken as 30 years, but the evaluation result is unsafe if the target period of usage is smaller; the target period of usage for historical buildings is suggested to chosen for 30 years considering the balance between safety and conservation comprehensively, which means assessing the seismic performance of the buildings every 30 years, earthquake action and seismic fortification measures should be adjusted at the same time. According to this principle, with the development of technology after 30 years, effective measures can be adopted to coordinate the contradiction between strengthening and conservation.

Performance objective is summation of each performance level under specific earthquake ground motion, which is divided into three levels in SEAOC Vision2000: basic objective, essential objective and safety critical objective (Fig. 4). Importance and historical values of the building is a significant foundation for choosing structural performance objective, especially for outstanding historical buildings. Historical buildings in Shanghai are divided into three levels and there are four kinds for conservation of outstanding historical buildings: (1) the building façade, structural system, plane layout and internal distinctive decoration are not allowed to be changed; (2) the building parts other than the building façade, structure system, plane layout and distinctive decoration is allowed to be retrofitted; (3) the internal part of the building is allowed to be changed, while the building façade and structure system must be preserved; (4) the building parts other than the main façade is allowed to be retrofitted. Refer to the policy that has been given in the current code, importance of historical buildings should be classified combined with the intrinsic value, damage condition and severity of damage consequence, then appropriate performance objective for the historical buildings with different important factors can be chosen.

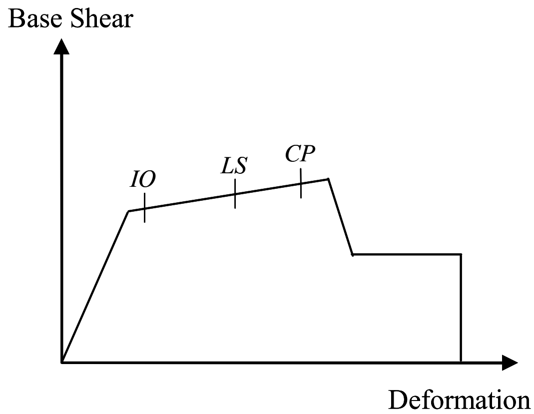

Figure 3: Limit deformation for different performance level

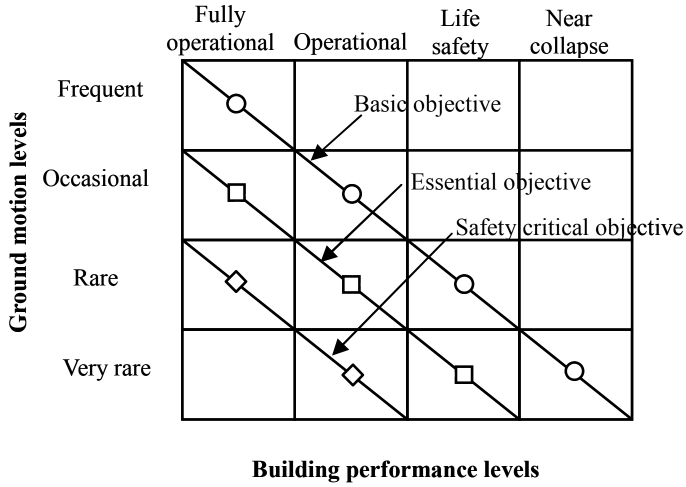

Figure 4: SEAOC Vision2000 performance objective

As existing buildings, suitable performance index should be chosen for historical buildings combined with its characteristic; the limit value of index should be relaxed properly to solve the contradiction between conservation and excessive strengthening according to the importance of the building. It can be achieved from two different paths: if target period of usage is determined by current code, then the performance index should be relaxed, for example, the first kind of conservation historical buildings can be regulated to arrive at operational state under frequent earthquake; the second kind of conservation building can be regulated to arrive at immediate occupancy state to distinguish the importance of the buildings; (2) if the target period of usage equal to 30 years, the limit value of performance index is determined by the current code.

Case Study The structural model mentioned above was chosen for pushover analysis, target period of usage was determined as 50 years and 30 years. The general finite element software Sap2000 is used in the analysis; two types of nonlinear hinges were specified for frame elements: moment hinges were placed to each end of the beams for rigid frame, the same hinges were placed to the middle of the beams for hinged frame; biaxial (PMM) hinges were placed near the top and bottom of the columns. The model was calculated without considering the contribution of infill masonry walls.

For the hinged frame model, angular drift between floors can not meet the requirement of seismic code. For the rigid frame model, if the target period of usage was taken as 30 years, results showed that only plastic hinges formed at the end of a few columns when attain the performance point, and the deformation meet the performance level of immediately occupancy; if the target period of usage was taken as 50 years, quantity of plastic hinges increased, only a few exceed the performance level of life safety. It can be determined that the structure is basically in elastic state. The integral seismic behavior of the rigid frame structure is better comparing to the hinged frame structure, and the calculation results are consistent with the response spectrum analysis results, but the columns can not satisfy the principle of strong column and weak beam if plastic hinges formed, and these members should be strengthened to increase the rigidity and improve integral seismic behavior of the structure.

Table 4: Angular Drift between floors of the building under earthquake

Floor	*Angular drift between floors of rigid frame model*		*Angular drift between floors of hinged frame model*	
	Target period of usage/30 years	*Target period of usage/50 years*	*Target period of usage/30 years*	*Target period of usage/50 years*
5	1/1926	1/1063	1/314	1/233
4	1/1079	1/597	1/237	1/175
3	1/827	1/457	1/207	1/152
2	1/667	1/366	1/216	1/159
1	1/943	1/521	1/434	1/314

Conclusions

Historical buildings belong to existing buildings, useful information of the structure should be collected; calculation equation of the bearing capacity of structural members and the load value should be adjusted accordingly.

Effective factors should be considered, including the interaction between structural members and nonstructural members, the main members and secondary members.

Performance-based seismic evaluation is a new effective way for seismic evaluation of historic buildings. To do so, the importance of historical buildings should be classified according to the conservation criteria, and then the performance objective should be determined.

Acknowledgements

This work was funded by the National Key Technology R & D Program of China (Grant No: 2006BAJ03A07).

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