PREDICTION OF EARTHQUAKE DAMAGE TO EXISTING BRICK BUILDINGS IN CHINA

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SUMMARY

Investigation of assessment of aseismic capacity and prediction of earthquake damage to existing multi-story brick buildings are illustrated in this paper. This study is based on the data of a great deal of earthquake damages to brick buildings during recent destructive earthquakes in China and their dynamic properties measured in sites. Generally, the synthetical index is used as criterion in prediction. The damage prediction may be carried out for earthquake intensities VI to X. The reliability of damage prediction generally is satisfactory. This method has been used in more than ten cities in China.

INTRODUCTION

Most of the existing civil buildings are brick construction in cities and towns in China, in which multi-story brick building is the main type of structure generally used for dwelling, school, hospital and office building. Owing to the damage and collapse of brick building, life and property suffered extremely serious losses during destructive earthquakes in late twenty years. Only in the City of Tangshan 933 multi-story brick buildings had collapsed and number tens of thousands of people had died during that earthquake. In recent years, therefore, the methodology of the assessment of earthquake resistance capacity of multi-story brick building was further studied and the prediction of earthquake damage was developed in order to provide a basis for disaster prevention planning and measures taken against earthquake for seismic hazard reduction. Method of prediction of damage is based on the experience of earthquake damage to a lot of multi-story brick buildings during past destructive earthquakes and mathematical model is taken according to usual way of aseismic design, so that it would be more convenient to use for engineering-technical personnel. The statistical relationships between damage and strength in around about 70000 wall pieces from almost 1000 floors of more than 400 buildings are used as the main criterion of prediction (Ref. 1. 2. 3), and then the effect of other elements of building structure and the influence of site condition are taken into account. The synthetical index is used to show the earthquake resistance capacity of building. The prediction of damage may be carried out for earthquake intensities VI to X. For prediction of damage in a region, not only the degree of damage of individual building, but also damage matrix which includes damage degree, intensity and probability and its distributive figures in such region are to be given. For prediction of damage to typical buildings, not only degree of

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damage, but the location and developing process of damage also should be represented.

Applying this method, prediction of earthquake damage to typical buildings has been developed in more than ten cities in China. Moreover, Bei-guan in Anyang, Henan Province was selected as an experimental station for the study on prediction of damage to existing multi-story brick buildings(Ref. 4).

CLASSIFICATION OF DAMAGE DEGREE AND MACROSCOPIC DAMAGE PROBABILITY

Based on the damage degree of main structure and secondary structure and the difficulty in prepairing, the predicted damage degree can be divided into six categories the same as the division used in nowadays, i.e.

Basically intact — no damage or very slight damage accidentally occurred in non-structural element. The earthquake damage index is $i = o$.

Slightly damaged — obvious damage found in the local part of the secondary structural element or few main structures slightly damaged. No effect on normal function of the building. In general, little repair work is necessary. In this case, we have $i = 0.2$.

Moderately damaged — secondary structure damaged generally, or damage occurred in many parts of the main structure. It still functions after local repair or strengthening. $i = 0.4$.

Seriously damaged — main structure damaged generally or part of the structure seriously damaged. Only after major repair, the building can be used again , or no repair significance. $i = 0.6$.

Partial collapse — partial collapse occurred in main structure or majority of collapse occurred in wooden roof, or most of collapse occurred in no bearing exterior longitudinal wall. $i = 0.8$

Total collapse — collapse occurred in entire floors or some upper floors or most of building $i = 1.0$.

Sometimes, the damage degrees were merged into three grades, the so called good (basically intact and slightly damaged), damaged (moderately and seriously damaged) and collapse (partial and total collapse).

The damage degree of multi-story brick building undergoing various intensities are roughly stated as follows:

VII — minority of buildings damaged, but majority of buildings basically intact or slightly damaged

VIII — about half of buildings damaged and a few buildings collapsed.

IX — majority of buildings damaged but minority collapsed.

X — majority of buildings collapsed.

In accordance with the data of more than seven thousands multi-story brick buildings subjected to VI to X intensities during Wulumuqi, Dunchuan, Yangjiang, Tonghai, Haicheng and Tangshan earthquake, the damage probabilities had been counted respectively and are listed in Tab. 1. It must be illustrated that most of these buildings were built on class II soil without aseismic

Tab. 1. Macroscopic damage probability of multistory brick building

	Intensity	VI		VII		VIII		IX		X		XI	
	Probability	M	D	M	D	M	D	M	D	M	D	M	D
damage degree	Basically intact	52.9	.20	41.0	.39	12.2	.56	1.4	1.2	0.4	1.9	0.3	3.7
	Slightly damaged	32.8	.25	27.6	.33	18.9	.49	10.1	1.7	10.5	1.4	1.6	2.6
	Moderately damaged	11.8	.70	17.3	.30	34.5	.28	28.9	.55	9.2	.96	5.6	2.0
	Seriously damaged	2.4	.90	13.0	.60	25.9	.31	37.3	.52	20.4	.38	11.5	.87
	Partial collapse	0		1.1	2.0	7.5	1.6	11.0	.70	16.4	.67	11.9	.79
	Total collapse	0		0		1.0	2.0	11.3	.95	43.1	.59	69.1	.41
Earthquake damage index average value		0.13		0.21		0.40		0.56		0.74		0.88	

Note: M — average value D — deviation coefficient

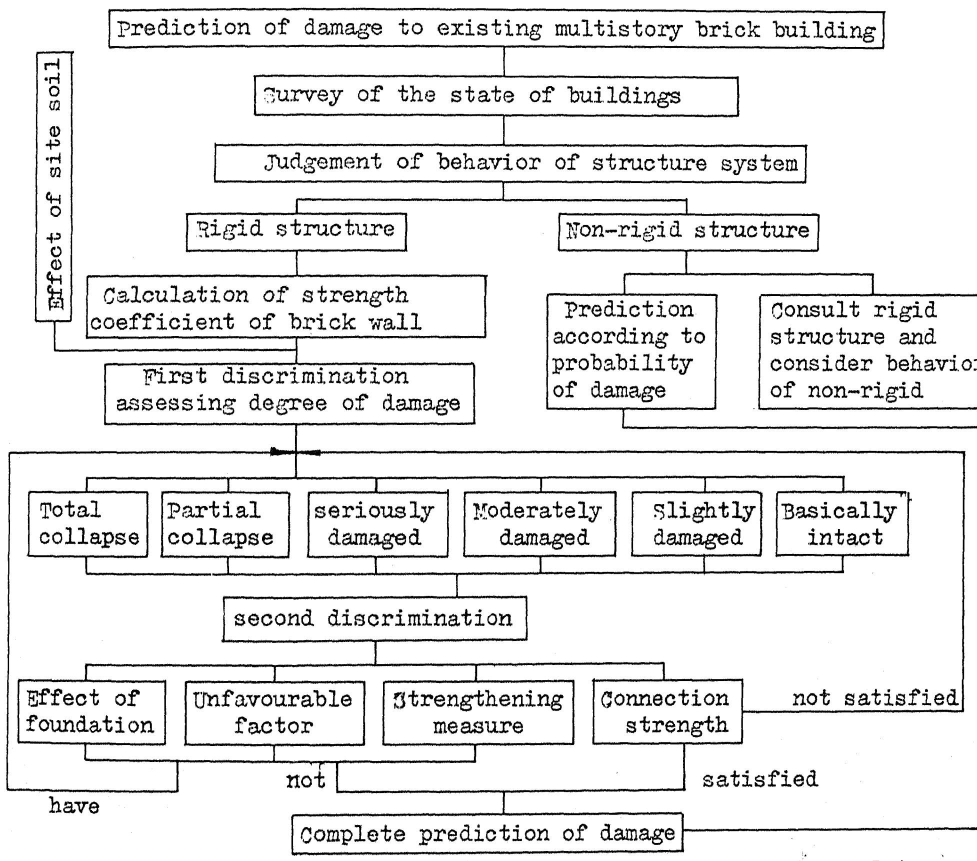

Fig. 1. Block diagram for prediction of damage to existing multistory brick building

design. The effects of site condition on damage have been reflected in the coefficient of variation of probability. Therefore, when these results are used to practice of prediction, defence intensity, number of buildings which were designed according to aseismic code and site condition of the predictive area need to be carefully considered.

THE BLOCK DIAGRAM AND PROCEDURE FOR THE PREDICTION OF EARTHQUAKE DAMAGE

Fig. 1 shows the block diagram for the prediction of damage to existing multi-story brick buildings. The prediction of damage may be approximately divided into three steps:

Judgement of Behavior of Structure System and Estimation of the Type of failure

Predicting damage to multi-story brick building, behavior of structure system needs to be determined in the first place. The multi-story brick building can be divided two categories, namely: rigid and non-rigid structure system. The behavior of structure system usually depends on the distance between transversal walls, rigidity of floors and roof as well as ratio of height to width of building. For rigid structure system, the natural vibrational modal is shearing-shaped. For non-rigid structure system, it is bending-shearing-shaped. The type of failure of rigid multi-story brick building generally is shearing shaped , i.e., it is characterized by the diagonal cracks running across the wall surface and the collapsed walls usually fell around the building with floor slabs decked up like pancakes. The non-rigid buildings generally show bending shape of failure. The quantity of non-rigid building is very fewer than rigid building and majority of them was built with wooden floor and roof long long ago.

Calculation of Earthquake Resistance Strength Coefficient of Brick Wall and Strength Discrimination

A vast amount of damage appearances indicate that earthquake damage of multi-story brick building often occurred in brick masonry, and ERC of which mainly depends on earthquake resistance strength of masonry. Therefore, earthquake resistance strength coefficient of wall element is used as a main criterion for the prediction of earthquake damage to such buildings. Generally speaking, ERC of wall element with the smallest strength coefficient is the weakest and the wall element is cracking first of all, and collapse of building starts from the floor with the smallest strength coefficient. For majorrity of multi-story brick building in China, prediction of damage has been completed by use of strength discrimination, in other words, the 3th step of prediction which follows is not requisite.

Second Discrimination, Synthetical Prediction of Earthquake Damage to Building

The damage degree had been estimated with earthquake resistance strength coefficient, at first, then, considering favorable or not favorable factors against earthquake, second discrimination is carried out and the final results of prediction should be given. The content can be stated roughly in 4 respects as follows:

(1) Bond between longitudinal and transversal walls.

When the connection strength between wall elements is greater than the earthquake resistance strength of wall, the connection would be considered as assurance. Thus, the earthquake resistance capacity depends only on the earthquake resistance strength coefficient of the wall proper. When the connection strength is less than earthquake resistance strength, the former should be used in prediction damage. For lack of bond between wall elements, overturning of the exterior longitudinal wall might be of frequent occurrence. The connection strength is assured by the bonding integrity of toothing of brick walls, the connecting reinforcement and the R. C. collar tie beam.

(2) Strengthening measures

The R.C. structural columns and collar tie beams are usually used as strengthening measure for multi-story brick buildings at present in China. The strengthening effect of them may be expressed as strengthening coefficient. But, the R.C. structural column together with collar tie beam must form a closed frame for brick wall. The strengthening effect of collar tie beam, besides strengthening connection strength, may be provided against partial collapse.

(3) Unfavorable factor on the structure (Ref. 5)

Assessing performance of the parts of structure in future earthquake, plenty experience on earthquake damages and judgment ability of engineering is usually demanded for a predictor. Some locations of structure should be carefully paid attention in case the failure of which would lead to collapse of the building. Usually, the unfavorable factors can be stated as follows:

a) When the center of rigidity of structure obviously deviates its center of gravity, there is effect of torsion on the building.

b) For attic story is smaller on the top of the roof of a building, the magnifying dynamic effect belongs to unfavorable fator. Damage to buildings having variation in its elevation often occurs in the protruding part and is generally heavier than the main building.

c) For buildings which possess a great disparity in rigidity distribution between parts of structure, or the configuration of building is complicated, the failure of location of structure should be considered due to no coordination of deformation of parts.

d)Partial collapse may be led due to breaking or less of stability of individual element bearing load, such as the independent brick column in entrance hall.

e) When the wooden roof is taken, damage to topmost story obviously becomes heavier due to lack of good integrity; when the level transversal force occurred by elements of roof is acting on the exterior walls, they may appear crack too early, even partial collapse. In this case, the ageing, the quality of construction and the materials of building must be considered for prediction of damage to existing brick buildings

(4) The effect of site condition and foundation.

It is a common knowledge that the influence of site on earthquake damage to brick building is evident, but to make a survey of site is even more difficult than structure itself on ground. The coefficient of site effect must be beforehand defined in accordance with the study on ground motion in the predictive region. For the class II soil, the coefficient may not be considered, i.e. the value equals 1. However, for backfill, unequal hardness or settlement probably appeared during earthquake, foundational soil, unstable hillside, river bank and unfavorable building site, it should be paid full attention that whether the treatment of base and foundation is proper and its effect to brick building during earthquake damage.

DISCRIMINATE FORMULA AND CRITERIA OF PREDICTION DAMAGE

The earthquake resistance capacity of multi-story brick building is expressed as a earthquake resistance index, i.e.

$$K = K^{I} \cdot K^{II}$$

where K^{I} is strength coefficient. It is expressed as the earthquake resistance strength coefficient K_{ij} of the jth brick wall element on the ith floor and the average earthquake resistance strength coefficient K_i of brick walls on the ith floor; both coefficients can be calculated as follows:

$$K_{ij} = \frac{(R\tau)_{ij}}{2\xi} \cdot \frac{A_{ij}}{k_{ij}} \cdot \frac{\sum_{j-1}^{m} k_{ij}}{\sum_{i-1}^{n} W_i} \cdot \frac{\sum_{i-1}^{n} W_i H_i}{\sum_{i-i}^{n} W_i H_i} \qquad K_i = \frac{m}{\sum_{j-1}^{m} \frac{1}{K_{ij}}}$$

where $(R\tau)_{ij}$ —— earthquake resistant shear strength of the jth wall element on the ith floor

2 —— Safety coefficient

ξ —— nonuniform shear stress coefficient on the wall section

A_{ij}, k_{ij} —— net cross-section area of the wall element and its rigidity for lateral drift

W_i —— lumped mass on the ith floor

H_i —— Height of the ith floor from the ground level

m —— number of wall elements in the direction of consideration (longitudinal or transversal)

n —— number of floors in the building

where K^{II} is second discriminating coefficient; it is expressed by

$$K^{II} = \frac{c\,e\,f\,g}{(1+a)(1+B)d}$$

where a —— coefficient of effect of the structural system; for rigid system, a = o, for non-rigid system a can be taken according to the following conditions: a = o.3 — 0.5 for top floor, a = – (0.1—— 0.3) for lower floor.

B —— coefficient of effect of torsion in the structure, its value can be determined by calculation.

c —— structure intensification coefficient when R.C. columns are placed in all intersection of both longitudinal and transversal walls, value of c can also be calculated; generally, cracking resistance coefficient taken c = 1.1, breaking resistance coefficient used as prediction for seriously damaged or collapse taken c = 1.3 – 1.5, strengthen effect of R.C. collar tie beam for only restraining partial collapse taken $c = 1.1 — 1.3$

d — dynamic amplification coefficient for small building on the house top can be taken as 2-3.

e — structure local unfavorable effect coefficient, taken $e \leq 1$

f — reduced coefficient owing to the ageing of the building, unsteady material and unskilful workmanship taken $f \leq 1$

g — local foundational effect coefficient, when the foundation and base is treated improperly taken $g = 0.3 — 0.9$

The corresponding relationship between damage degrees and earthquake resistance strengths of multi-story brick building were obtained statistically based on a vast amount of data collected in different district of various intensity during many destructive earthquakes. The discriminating criteria of predicting damage are listed in Table 2. Such criteria are provided for the damages of prediction of building on class II soil. If the site soils are not Class II, the characteristic of ground motion should be predicted at first, in order to give site effect coefficient and then after putting it into discriminating formula, prediction of damage carries out.

EXAMINATION OF RELIABILITY ON PREDICTION OF EARTHQUAKE DAMAGE

For the prediction of earthquake damage to existing multi-story brick building, even if the structure and the site soil has been clearly surveied, the result of prediction can not absolutely correct yet due to the indefinition of the earthquake and the indefinition of the relationship between damage and structure or site soil.

For 348 buildings sufferred from Tangshan earthquake or Haicheng earthquake, predicting damage degree have been contrasted with real damage degrees during the earthquake. The result is listed in Table 3. Thus it has been obtained that if only strength discrimination is used to predict damage to multi-story brick building, for damage degree classified as six grades, the coincidence ratio is 69.5%, the average deviation is 0.39 grade; for classified as three grades, the ratio is 87.6%, the deviation is 0.13 grade. After second discrimination coefficient had been applied, the coincidence ratio is 88.5% and 95.4% for grades classified as six and three respectively, the corresponding average deviation being 0.14 and 0.05 grade. These results indicate that the method of prediction of earthquake damage to multi-story brick buildings generally is reliable.

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Tab. 2 ERC index used as a criterion in the prediction of damage to multi-story brick buildings

Intensity		VI	VII	VIII	IX	X
K_o	Range	0.05–0.12	0.12–0.19	0.19–0.26	0.26–0.40	0.40–0.70
	Mean value	0.08	0.15	0.22	0.33	0.55
K_{io}	Range		0.04–0.06	0.06–0.09	0.09–0.13	0.13–0.23
	Mean value		0.05	0.07	0.11	0.18
Damage degree	Basically intact	$(K_{ij}^I \cdot K_{ij}^{II})_{min} \geqslant K_o$				
	Slightly damaged	$(K_{ij}^I \cdot K_{ij}^{II})_{min} < K_o$, $(K_i^I \cdot K_i^{II})_{min} \geqslant K_o$				
	Moderately damaged	$0.6K_o \leqslant (K_i^I \cdot K_i^{II})_{min} < K_o$				
	Seriously damaged	$K_{io} \leqslant K_i^I \cdot K_i^{II} < \begin{cases} 0.6K_o & (no \geqslant 1) \\ 0.7K_o & (no > n/2) \\ 0.8K_o & (no > 2n/3) \\ 0.9K_o & (no \geqslant 3n/2) \end{cases}$				
	Partial collapse	no bearing wall $(K_i^I \cdot K_i^{II})_{min} < K_{io}$ bearing wall element $(K_{ij}^I \cdot K_{ij}^{II})_{min} < K_{io}$				
	Total collapse	bearing wall $(K_i^I \cdot K_i^{II})_{min} < K_{io}$				

Note:

K_o – critical value for cracking of brick wall

K_{io} – critical value for collapse of brick building

K_{ij}^I – earthquake resistance strength coeff. for the jth wall element on the ith floor

K_{ij}^{II} – second discriminating coeff. for the jth wall element on the ith floor.

K_i^I – average strength coeff. for the walls (longitudinal or transversal walls) on the ith floor

K_i^{II} – second discriminating coeff. for the ith floor

n – number of floors in the building

no – number of ERC which do not satisfy the requirement. If ERC of all floors do not satisfy at all, then no=2n.

Tab.3 Examine of predicting damage to multistory brick building

(1) Strength discrimination

Predict \ Real		Good		Damaged		Collapse	
		B	Sl	M	Se	P	T
Good	B	19	5	3			
	Sl	3	25	7	5	1	
Damaged	M	2	7	51	25	3	2
	Se		2	9	73	3	2
Collapse	P				1	17	13
	T				6	7	57

(2) Synthetical discrimination

Predict \ Real		Good		Damaged		Collapse	
		B	Sl	M	Se	P	T
Good	B	19	1	1			
	Sl	3	29	1			
Damaged	M	2	8	59	4		
	Se		1	9	102		
Collapse	P				0	27	2
	T				4	4	72

Note:
B– Basically intact
Sl–Slightly damaged
M– Moderately damaged
Se–Seriously damaged
P– Partial collapse
T– Total collapse