PREDICTION OF EARTHQUAKE DAMAGE
TO EXISTING BRICK BUILDINGS IN CHINA

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SUMMARY

Investigation of assessment of aseismic capacity and prediction of earth-
quake 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 suffer-
ed 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 earth-
quake. 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 build-
ing. 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 Uyang, 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 preparing, 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 = 0.
- 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 VII to X intensities during Wulumuqi, Dunhuang, Yangjiang, Tonghai, Haicheng and Tangshan earthquakes, 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

<table>
<thead>
<tr>
<th>Damage degree</th>
<th>Probability (%)</th>
<th>Intensity</th>
<th>VI</th>
<th>VII</th>
<th>VIII</th>
<th>IX</th>
<th>X</th>
<th>XI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>M</td>
<td>D</td>
<td>M</td>
<td>D</td>
<td>M</td>
<td>D</td>
<td>M</td>
</tr>
<tr>
<td>Basically intact</td>
<td>52.9</td>
<td>41.0</td>
<td>39</td>
<td>12.2</td>
<td>.58</td>
<td>1.4</td>
<td>1.2</td>
<td>0.4</td>
</tr>
<tr>
<td>Slightly damaged</td>
<td>32.8</td>
<td>25.7</td>
<td>27</td>
<td>33</td>
<td>18.9</td>
<td>9.4</td>
<td>1.7</td>
<td>10.5</td>
</tr>
<tr>
<td>Moderately damaged</td>
<td>11.8</td>
<td>70.1</td>
<td>17</td>
<td>3.0</td>
<td>34.5</td>
<td>.28</td>
<td>.28</td>
<td>.55</td>
</tr>
<tr>
<td>Seriously damaged</td>
<td>2.4</td>
<td>.90</td>
<td>13</td>
<td>.0</td>
<td>6.0</td>
<td>25.9</td>
<td>.31</td>
<td>.37</td>
</tr>
<tr>
<td>Partial collapse</td>
<td>0</td>
<td>1.1</td>
<td>2.0</td>
<td>7.5</td>
<td>1.6</td>
<td>11.0</td>
<td>.70</td>
<td>16.4</td>
</tr>
<tr>
<td>Total collapse</td>
<td>0</td>
<td>0</td>
<td>1.0</td>
<td>2.0</td>
<td>11.3</td>
<td>.95</td>
<td>43.1</td>
<td>.59</td>
</tr>
<tr>
<td>Earthquake damage index average value</td>
<td>0.13</td>
<td>0.21</td>
<td>0.40</td>
<td>0.56</td>
<td>0.74</td>
<td>0.88</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: M — average value    D — deviation coefficient

Prediction of damage to existing multistory brick building

[Diagram]

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, defense intensity, number of buildings which were designed according to seismic 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 vibration 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 SRC 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, SRC 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 majority 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 factor. 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 earthquakes, foundational soil, un-
stable hillsides, 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 resis-
tance strength coefficient \( K_{ij} \) of the \( j \)th brick wall element on the \( i \)th floor and
the average earthquake resistance strength coefficient \( K_i \) of brick walls on
the \( i \)th floor; both coefficients can be calculated as follows:

\[
K_{ij} = \frac{\sum_{k=1}^{m} \Sigma_{W;H_i}}{k_{ij}} \cdot \frac{\sum_{j=1}^{n} W;H_i}{W_i} \cdot \frac{\sum_{i=1}^{m} K_{ij}}{K_i}
\]

where \((R\tau)_{ij}\) —— earthquake resistant shear strength of the \( j \)th wall element
on the \( i \)th floor

\( 2 \) —— Safety coefficient

\( \delta \) —— nonuniform shear stress coefficient on the wall section

\( A_{ij}, k_{ij} \) —— net cross-section area of the wall element and its rigid-
ity for lateral drift

\( W_i \) —— lumped mass on the \( i \)th floor

\( H_i \) —— Height of the \( i \)th 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

\[ K^{II} = \frac{c \cdot e \cdot f \cdot g}{(1+a)(1+b)} \]

where \( a \) —— coefficient of effect of the structural system; for rigid system,
\( a = 0 \), for non-rigid system \( a \) can be taken according to the
following conditions: \( a = 0.3 - 0.5 \) 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 co-
efficient used as prediction for seriously damaged or collapse taken
\( C = 1.3 - 1.5 \), strength 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 surveyed, the result of prediction can not absolutely correct yet due to the indefiniteness of the earthquake and the indefiniteness of the relationship between damage and structure or site soil.

For 348 buildings suffered 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 94.4\% 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.

REFERENCES

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

<table>
<thead>
<tr>
<th>Damage degree</th>
<th>Intensity</th>
<th>VI</th>
<th>VII</th>
<th>VIII</th>
<th>IX</th>
<th>X</th>
</tr>
</thead>
<tbody>
<tr>
<td>K₀ range</td>
<td>0.05-0.12</td>
<td>0.12-0.19</td>
<td>0.19-0.25</td>
<td>0.26-0.40</td>
<td>0.40-0.70</td>
<td></td>
</tr>
<tr>
<td>Mean value</td>
<td>0.08</td>
<td>0.15</td>
<td>0.22</td>
<td>0.33</td>
<td>0.55</td>
<td></td>
</tr>
<tr>
<td>Kᵢ,Ⅰ range</td>
<td>0.04-0.06</td>
<td>0.06-0.09</td>
<td>0.09-0.13</td>
<td>0.13-0.23</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean value</td>
<td>0.05</td>
<td>0.07</td>
<td>0.11</td>
<td>0.18</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basically intact</td>
<td>(kᵢ,Ⅰ - kᵢ,Ⅱ) &lt; K₀, (kᵢ,Ⅰ - kᵢ,Ⅱ) &gt; K₀</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slightly damaged</td>
<td>(kᵢ,Ⅰ - kᵢ,Ⅱ) &lt; K₀, (kᵢ,Ⅰ - kᵢ,Ⅱ) &gt; K₀</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moderately damaged</td>
<td>0.6K₀ ≤ (kᵢ,Ⅰ - kᵢ,Ⅱ) &lt; K₀</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seriously damaged</td>
<td>K₁₀ ≤ kᵢ,Ⅰ &lt; kᵢ,Ⅰ, (kᵢ,Ⅰ - kᵢ,Ⅱ) &lt; K₁₀</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Partial collapse</td>
<td>no bearing wall (kᵢ,Ⅰ - kᵢ,Ⅱ) &lt; K₁₀</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total collapse</td>
<td>bearing wall (kᵢ,Ⅰ - kᵢ,Ⅱ) &lt; K₁₀</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note:

- kᵢ,Ⅰ - critical value for cracking of brick wall
- kᵢ,Ⅰ - critical value for collapse of brick building
- kᵢ,Ⅱ - earthquake resistance strength coeff. for the jth wall element on the ith floor
- kᵢ,Ⅱ - second discriminating coeff. for the jth wall element on the ith floor
- kᵢ,Ⅰ - average strength coeff. for the walls (longitudinal or transversal walls) on 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=n.

### Tab. 3 Examine of predicting damage to multi-story brick buildings

#### (1) Strength discrimination

<table>
<thead>
<tr>
<th>Damage degree</th>
<th>Good</th>
<th>Damaged</th>
<th>Collapse</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>19</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>SL</td>
<td>3</td>
<td>25</td>
<td>7</td>
</tr>
<tr>
<td>M</td>
<td>2</td>
<td>7</td>
<td>51</td>
</tr>
<tr>
<td>Se</td>
<td>2</td>
<td>9</td>
<td>73</td>
</tr>
<tr>
<td>P</td>
<td>1</td>
<td>17</td>
<td>13</td>
</tr>
<tr>
<td>T</td>
<td>6</td>
<td>7</td>
<td>57</td>
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</tbody>
</table>

#### (2) Synthetical discrimination

<table>
<thead>
<tr>
<th>Damage degree</th>
<th>Good</th>
<th>Damaged</th>
<th>Collapse</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>19</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>SL</td>
<td>3</td>
<td>29</td>
<td>1</td>
</tr>
<tr>
<td>M</td>
<td>2</td>
<td>8</td>
<td>59</td>
</tr>
<tr>
<td>Se</td>
<td>1</td>
<td>9</td>
<td>102</td>
</tr>
<tr>
<td>P</td>
<td>0</td>
<td>27</td>
<td>2</td>
</tr>
<tr>
<td>T</td>
<td>4</td>
<td>4</td>
<td>72</td>
</tr>
</tbody>
</table>

Note:

- B - Basically intact
- SL - Slightly damaged
- M - Moderately damaged
- Se - Seriously damaged
- P - Partial collapse
- T - Total collapse