EMPIRICAL RELATIONSHIP BETWEEN DAMAGE TO MULTISTORY BRICK BUILDINGS AND STRENGTH OF WALLS DURING THE TANGSHAN EARTHQUAKE

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SUMMARY

In this paper, the earthquake resistance strength of multistory brick buildings is calculated, and the result is compared to the actual damage during the Tangshan earthquake. Statistical analysis shows that there exists a critical value of story aseismic coefficient K_{i0}. When the aseismic coefs. of all stories of a building are greater than this value, the buildings will not collapse generally. There also exists a similar critical value, K_0, for the cracking of a wall element. K_{i0} values for Tangshan and K_0 values for areas of different intensities are given in the paper.

INTRODUCTION

On July 28, 1976 at 03:42 a. m. (Beijing time), a strong earthquake of magnitude 7.8 occurred in Tangshan, Hebei Province, China. The macroscopic epicenter was located in the city of Tangshan. The intensity in the meizoseismal area was 11. The whole metropolitan area was enclosed within the isoseismal of intensity 10. The shock struck the whole Tangshan region as well as Tianjin and Beijing. Life and property loss were great.

Multistory brick building is one of the main types of structures generally used for dwelling house, school, hospital and office building in cities and towns in China. In the meizoseismal area of the Tangshan earthquake, a great amount of such buildings collapsed, leading to heavy casualties, especially in the city of Tangshan. In other areas, such buildings also suffered different degrees of damage, affecting rapid restoration of production and normal living condition. Hence, it is very important in the field of earthquake engineering of China to sum up earnestly the lessons learned from the damage to the multistory brick buildings as well as to have an understanding and raise its earthquake resistant capability.

DAMAGE TO MULTISTORY BRICK BUILDINGS

Damage in the urban area of Tangshan City The city of Tangshan is divided into two parts by the railway. In the eastern part of the city, Dou River runs through from north to south, while to the north there lies Dachen Hill, Fenghuang Hill and Jiajia Hill, all of naked limestone of Ordovician System. A surface fault trace goes right through the southern part of the city. There were 1187 multistory brick buildings in the city before the quake, most of them being of two or three stories and the rest four or five stories with a few of seven or eight stories. Such buildings were generally built of brick bearing walls with reinforced concrete floor and roof, only a few were of stone walls or wooden roof and floor. After the quake, most of the buildings were collapsed, only a few survived with cracked walls and obvious dislocation. Fig. 1 shows the distribution of collapse ratio for multistory brick buildings in Tangshan City. It is seen from the figure

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that for buildings to the south of the railway and in the downtown along Xinhua St., the collapse ratio is above 90%, while for those near Dacheng Hill, the collapse ratio is below 30%. For buildings on soft soil sites with intercalation of silty clay along Dou River, most of them did not collapse, except those in the area where the causative fault passed. Among multistory brick buildings in the city, 78% were totally or partially collapsed, 19% seriously or moderately damaged and only 3% survived with slight damage (see Table 1). According to the type of structures, the collapse ratio is 74% for buildings with brick walls and reinforced concrete floors, 97% for buildings with wooden floor and roof, and 93% for buildings with stone walls. As to buildings with precast and cast-in-place reinforced concrete floor elements, the collapse ratio cover 77% and 73%, respectively.

Damage statistics in other areas Outside the city of Tangshan, the common damage pattern is shearing cracks caused by the principal tensile stresses in the walls and, sometimes fall of wall corners in the more serious cases. Table 1 also lists the damage ratio for multistory brick buildings in living quarters of Fangezhuang, railway areas of Beijiadian, Luan County, Chang Li and Qinhuangdao etc. Location of these cities or towns is given in Fig. 2, all located in the east of the long axis of the isoseismals. It is obvious that the damage to multistory brick buildings decreased with the increase of epicentral distance (see damage index I in the Table 1).

Damage patterns Based on the post-earthquake surveys, the damage patterns of rigid multistory brick buildings due to the effect of seismic inertia force may be classified into three categories as follows:

a) Shear failure in diagonal tension. For the majority of collapsed buildings, the walls were cracked by diagonal tension at first, and then displaced, dislocated, crushed, fell and eventually lost their bearing capacity, leading to the collapse of the whole building. In such cases, the collapsed walls usually fell around the building, with floor slabs decked up like pancakes. Some buildings totally collapsed, while in some buildings, the upper stories collapsed with lower stories survived.

b) Loss of bond between wall elements. This kind of failure was often found due to the weakness of the connections between exterior longitudinal walls and interior transverse walls. Cracks often formed in the wall corners. Usually only exterior walls were overturned, due to the loss of stability. Sometimes, the exterior walls were firstly collapsed, and then the interior transverse walls overturned with roof or floor slabs falling on them.

c) Failure by direct horizontal shear. The failure is generally indicated by horizontal fissures on the wall, and cracks between floor slab and walls. Sometimes, displacement and dislocation occurred. For serious cases, part of precast floor slabs fell down, but no collapse due to too great dislocation was found.

The number of non-rigid multistory brick buildings was not so many. The damage features, different from that of the rigid one, can be characterized by the failure of off-plane bending and the occurrence of horizontal fissures on walls. For serious cases, the brick masonry overturned, and even collapsed.

Method of calculation Earthquake resistance of a multistory brick building depends mainly on the aseismic strength of the walls. A coefficient, called aseismic coef. K_{ij} , is used to represent the lateral resistance of a wall element j in the story i.

In aseismic design, we first calculate the main seismic load as follows:

$$Q_0 = K\sum_{i=1}^{n} W_i$$

where W_i is the weight of lumped mass at the i-th story and K is an equivalent static coefficient. The corresponding earthquake load at i-th story is taken as

$$P_i = Q_0 W_i H_i / \sum_{i=1}^{n} W_i H_i$$

where H_i is the height of W_i calculated from the ground surface. Then distribute the load to the wall elements according to their rigidity (k_{ij}), viz.

$$Q_i = (k_{ij}/\sum_i k_{ij})\sum_{i=i}^{n} P_i$$

Finally, following the aseismic code of China, we check the shear strength of the walls, $(R_\tau)_{ij}$, according to the following formula, taking the safe factor as 2

$$(R_\tau)_{ij} \geqslant 2\,\xi_{ij} Q_{ij} / A_{ij}$$

where A_{ij} is the net cross sectional area of the wall element, and ξ_{ij} the non-uniformity coef. of shear stress, is 1.5.

Reversing the above procedure, the shear strength of wall elements of a building, is calculated forst, and then according the above formulas, the aseismic coef. is calculated with K instead of K_{ij} . Thus

$$K_{ij} = (R_\tau)_{ij} \quad A_{ij}\sum_{j=1}^{m} k_{ij}\sum_{i=1}^{n} W_i H_i / (2\,\xi_{ij} k_{ij} \sum_{i=1}^{n} W_i \cdot \sum_{i=i}^{n} W_i H_i)$$

For a certain building, K_{ij} apparently depends on the weight of the building, the cross-sectional area and the shear strength of the element j, and serves as an index of its resistance to earthquake. Coef. K_{ij} indicates the max. K of seismic load on the building that can be sustained by the intact wall element.

We have calculated a large number of K_{ij}'s of existing wall elements in damaged areas of certain previous earthquakes. The results indicate that under certain earthquake intensities there is a critical value of K_{ij}. This value is termed as "cracking resistance coefficient K_0". When K_{ij} of the wall is greater than K_0, the wall will not crack.

Moreover, a value K_i , for a given story i can be obtained by averaging the weighted values K_{ij} of all transverse or longitudinal walls in story i to indicate the earthquake resistance of that story. Such average value may be called as "story aseismic coefficient" and is equal to

$$K_i = \sum_{j=1}^{m} \frac{K_{ij} \quad k_{ij}}{(R_\tau)_{ij} A_{ij}} \Big/ \sum_{j=1}^{m} \frac{k_{ij}}{(R_\tau)_{ij} A_{ij}}$$

The results of calculation show that there is also a critical value of K_i. We name this value as "collapse resistance coef. K_{i0}". When the aseismic coefs. K_i of all stories of a building are greater than K_{i0} , the building will not collapse generally.

Selection of buildings for calculation Aseismic coefs. of 301 buildings located in the effected area of the Tangshan earthquake are calculated, including 65953 wall elements from 883 stories (see Table 2). 14 zones in the urban area of Tangshan are chosen for the study according to the classification of soil and arrangement of blocks (see Fig. 3). Detailed damage inspections were made to all multistory brick buildings located in the small zones outlined by solid lines as shown in Fig. 3. For the zones outlined by dotted lines, we only inspected the cracked but yet existed buildings in the south of the railway and some chief buildings along the Xinhua St. The aseismic coefs. are calculated for all multistory brick buildings with brick walls and reinforced concrete floors in the aforementioned 14 zones, Fangezhuang, Beijaidian, Luan County and Chang Li etc. In the cities of Tianjin and Qinhuangdao, only a few typical structures were chosen for calculation. In calculation, some buildings with wooden roof are chosen, but the upper story is omitted in the analysis. All the non-rigid brick buildings are excluded.

Analysis of results Fig. 4 shows the relation between damage and the story aseismic coef. K_i of the building on the site of Class II. In this figure, only K_i of the lowest collapsed stories are plotted for the totally destroyed buildings and buildings in which only the upper stories collapsed, while for the cracked buildings, the relation between damage and K_i of all stories is plotted. K_i of transverse walls in the same story are plotted on the top, while those of longitudinal walls are plotted below. A line is drawn between these two K_i's. It is evident from Fig. 4 that in the north of railway, those buildings, having K_i greater than 0.25, did not collapse, and in the south, K_i of few survived buildings was also greater than 0.25. In Fig. 5, K_i values for the small zones 1-6 are classified into "collapsed" and "uncollapsed". The cumulative frequency curve for "collapsed" is drawn from right to left, while that for "uncollapsed" is drawn from left to right. The value on the abscissa where the two curves intersect is K_{i0}; and that on the ordinate represents the discrepancy. From Fig. 5, the collapse aseismic coef. K_{i0} is 0.24 with the discrepancy 7.5%. From Fig. 4, K_{i0} value has a tendency of decreasing from south to north. K_{i0} decreases to 0.19 in the upmost north zone. The cracking resistance coef. is about 0.7 for the north of the railway.

Fig. 6 shows the similar relation (as shown in Fig. 4) for buildings built on rock in the hill area and its surrounding. In the figure, not only the relation between K_i and damage (denoted by large symbols), but also the relation between K_{ij} of wall elements and damage (denoted by small symbols) are shown, for buildings built on bedrock. The cracking resistance coef. 0.23 with the discrepancy 17.7% is obtained from K_{ij} of the cumulative frequency curves for "cracked" and "uncracked" wall elements as shown in Fig.7. And for buildings at the toe of hill, the cracking critical value is not obvious, being about 0.24-0.33, possibly affected by the variation of thickness of overlying soil.

Fig. 8 gives the same relations for buildings located along banks of the Dou River. The damage is conspicuously reduced in comparison with the site of Class II. In calculating zones, most of the buildings were uncollapsed with cracks on walls, but the cracking critical value is not obvious either. In the zones north of railway, K_0 is about 0.20-0.34, while in the zones south of railway, K_0 varies in a wider range. It is quite possible that the critical value of cracking decreases with increase in depth of the intercalation of silty clay.

In the seismic areas long away from Tangshan, such as Fangezhuang, Beijiadian, Luan County, Chang Li, Qinhuangdao and Tianjin, values of K_0 were calculated. It may be seen that cracking resistance coef. decreases with the increase of the epicentral distance. This is in agreement with the attenuation of intensity. Fig. 9 gives the curves showing relation between K_0 and the epicentral distance and the regression equation is as follows:

$$K_0 = 2.1\Delta^{-0.6}$$

the coef. correlation of which is 0.98.

From Fig. 9, we get K_i for different intensities as follows: less than 0.12 for intensity 6, 0.12-0.19 for intensity 7, 0.19-0.26 for intensity 8, 0.26-0.40 for intensity 9 and 0.40 for intensity 10. The above results are obtained from the Tangshan earthquake. For certain previous earthquakes, the calculated results of K_0 are in agreement with those given above. For the Haicheng earthquake, K_0 values are 0.28 and 0.30 respectively for two towns in area of intensity 9, 0.23 for a town in area of intensity 8, and 0.14 for a city in area of intensity 7. For the Yangjiang earthquake, K_0 is 0.17 for intensity 7, while for the Wulumuqi earthquake it is 0.12 for intensity 7 and for the Dongchuan earthquake, it is 0.22 for intensity 8.

Of course, there exists discrepancy between the relationships of damage and the aseismic coef. For value K_0 , the discrepancy is generally greater in the area of higher intensity than in the area of lower intensity, about 10% for intensity 7, about 20% for intensity 9.

CONCLUSIONS

Based on the results given above, we may conclude that: a) In the aseismic design of multistory brick building, two requirements should be kept in mind. Firstly, the building should not crack in the predicted moderate earthquake. Secondly, the building should not collapse in an unexpected earthquake of higher intensity even 1-2 grades higher than the expected intensity. b) Those carefully designed multistory brick buildings can survive in an earthquake of intensity 10. In fact, those buildings with K_i greater than 0.25 have all survived without collapse in the area north of railway in Tangshan. c) Values of K_0 obtained from the Tangshan earthquake coincide fairly well with those obtained from the other previous destructive earthquake. So K_0 may be used as a design parameter and also as a quantitative measure of earthquake intensity. d) Damage to multistory brick buildings in Tangshan reflected the effect of site conditions. There were two anomalous areas. Rock sites and soft soil sites with intercalation of silty clay are both favourable to such buildings. e) Collapse of multistory brick buildings was generally induced by the shear cracking in diagonal tension of bearing walls, followed by off-set of brick masonry, fracture of walls, and ultimately, loss of bearing ability of walls. The calculating method in this paper is established according to this type of failure.

Finally, it should be noted that the above conclusions are drawn from the specific features of Tangshan earthquake. Generalization of conclusions to other cases should be made carefully. However, the behaviors of rigid brick masonry buildings in meizoseismal areas for different soil conditions and the damage attenuation along the long-axis of the isoseismal provided in this paper also give some information for the study of the ground motion in the Tangshan earthquake.

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Table 1 Statistical of investigation on damage to multistory brick buildings in the Tangshan earthquake

Name of investigated location	Number of buildings	Degree of damage												damage index
		destroyed i = 1		collapsed i = 0.8		seriously damaged i = 0.6		moderately damaged i = 0.4		slightly damaged i = 0.2		practically undamaged i = 0		$I=\frac{\sum in}{N}$
	N	n	%	n	%	n	%	n	%	n	%	n	%	
Tangshan	1187	788	66.4	143	12	155	13.1	71	6	26	2.2	4	0.3	0.87
Pangezhuang	30	0	0	0	0	21	70	7	23	0	0	2	7	0.51
Beijiadian	20	0	0	2	10	3	15	14	70	1	5	0	0	0.46
Luan county	15	0	0	0 (2)	0 (13)	4 (4)	27 (27)	3 (3)	20 (20)	6 (4)	40 (27)	2 (2)	13 (13)	0.32 (0.40)
Chang li	17	0	0	0	0	1	6	5	29	4	24	7	41	0.20
Qinhuangdao	470	0	0	0	0	3	0.6	52	11.1	201	42.8	214	45.5	0.31
Total number	1739	788		145		187		152		238		229		

Values in parenthese are the damage ratios in an aftershock of magnitude 7.1

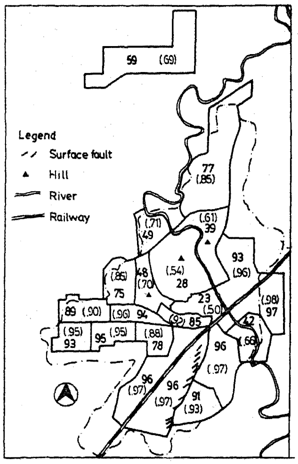

Fig. 1 Distribution of collapse ratio for multistory brick buildings in Tangshan City (values in parenthese are the damage index I)

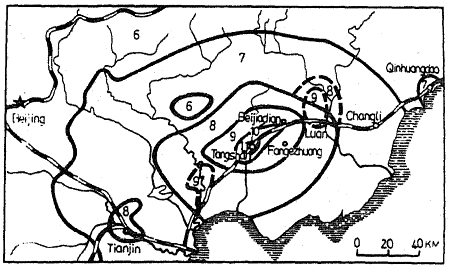

Fig. 2 Distribution of intensity in the Tangshan earthquake

Table 2 Total number of buildings taken in the calculation in the Tangshan earthquake

name of town or city	building	story	piece of wall
Tangshan	220	639	49573
Fangezhuang	15	44	2145
Beijiadian	17	49	2364
Luan County	10	23	2110
Chang Li	9	24	2447
Qinhuangdao	14	40	3086
Tianjin	16	64	4228
Total number	301	883	65953

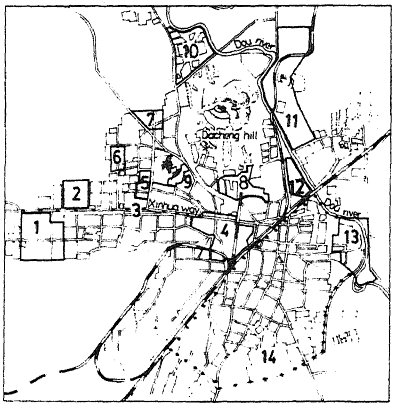

Fig. 3 Distribution of investigated zones in Tangshan City

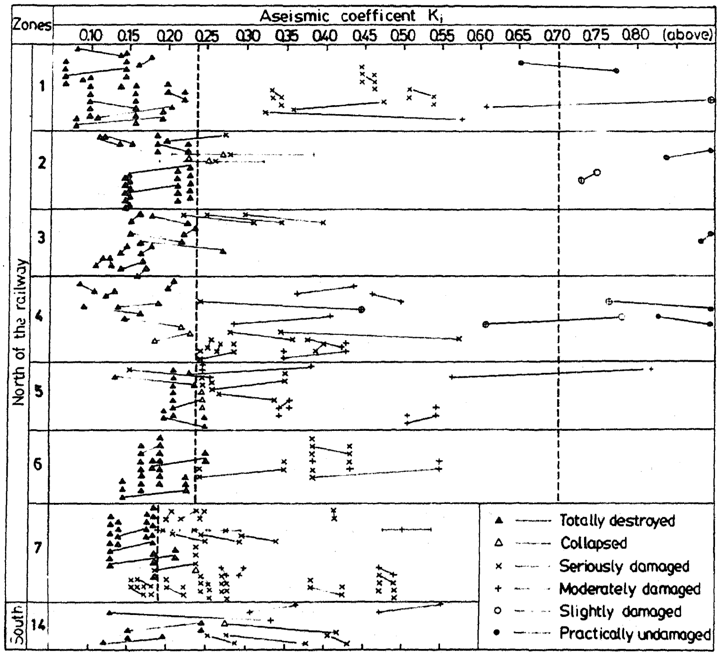

Fig. 4 Relation between damage and the aseismic coef. of multistory brick buildings on Class II Soil in Tangshan City

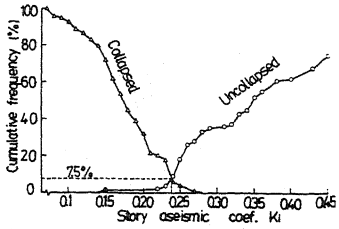

Fig. 5 Cumulative frequency curves for K_i Values of collapsed and uncollapsed buildings in the zones 1-6 of Tangshan City

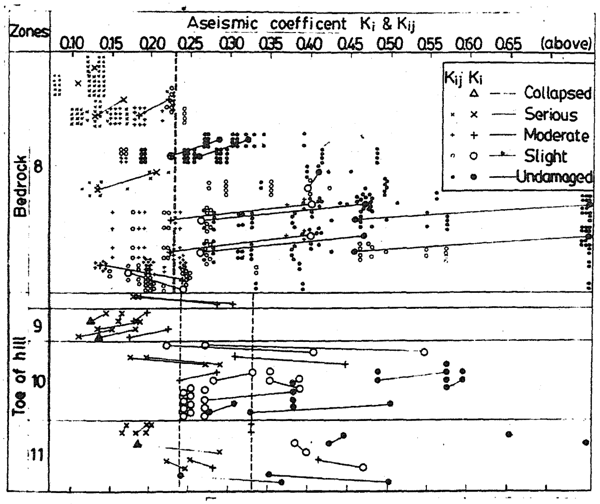

Fig. 6 Relation between damage and the aseismic coef. to multistory brick buildings on bedrock and on the near thin soil layer in Tangshan City

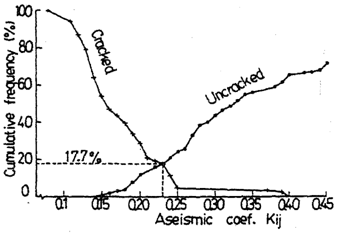

Fig. 7 Cumulative frequency curves for K_{ij} Values of cracked and uncracked walls built on bedrock in Tangshan City

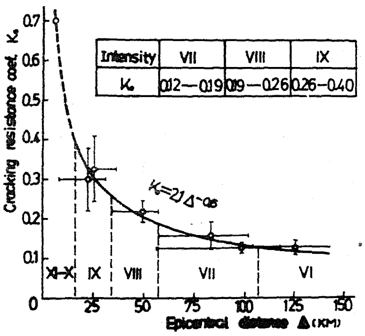

Fig. 9 Relation between the cracking resistance coef. of multistory brick buildings and epicentral distance in the Tangshan earthquake

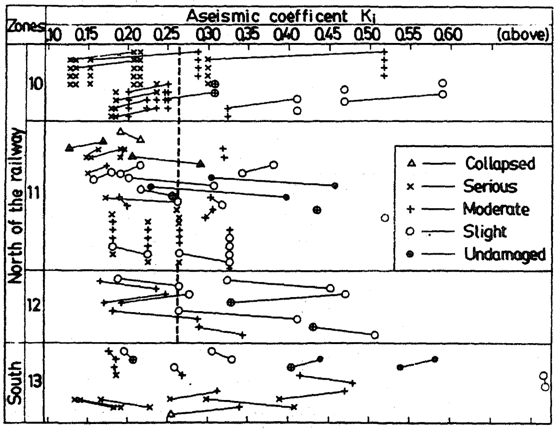

Fig. 8 Relation between damage and the aseismic coef. of multistory brick buildings along the Dou River in Tangshan City