

Zeitschrift: IABSE reports = Rapports AIPC = IVBH Berichte
Band: 67 (1993)

Artikel: Strength evaluation of existing masonry structures
Autor: Zhou, Xinggang
DOI: <https://doi.org/10.5169/seals-51370>

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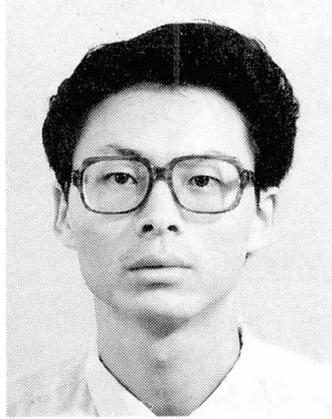
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Strength Evaluation of Existing Masonry Structures
Evaluation de la résistance de constructions en brique
Festigkeitsermittlung für bestehende Mauerwerksbauten

Xinggang ZHOU
Research Assist.
Yantai University
Yantai, China



Zhou Xinggang, born in 1963, received his engineering master's degree from Tsinghua University, China in 1989. Now he is a research assistant in Civil Engineering.

SUMMARY

According to experimental data and theoretical analysis, the relationship between strength and rigidity, rigidity deterioration, accumulated deformation energy in earthquake damage of masonry structures are studied. Methods are suggested that show how to evaluate the strength of masonry structures in serviceability state, and how to predict and evaluate the damage degree of masonry structures by earthquakes.

RÉSUMÉ

Sur la base de données d'essai et d'analyses théoriques, l'article étudie la relation entre la résistance de constructions en brique et la rigidité, la détérioration de rigidité, l'énergie de déformation accumulée lors de séismes. Des méthodes sont proposées pour l'évaluation de la résistance et de l'aptitude au service de constructions en briques, ainsi que pour l'évaluation de dommages possibles lors de séismes.

ZUSAMMENFASSUNG

Anhand experimenteller Ergebnisse und theoretischer Überlegungen, wird der Zusammenhang zwischen Festigkeit und Steifigkeit sowie des Steifigkeitsabfalls mit der kumulierten Verformungsenergie bei Erdbebenschäden an Mauerwerksbauten studiert. Es werden Verfahren vorgeschlagen, wie aus dem Gebrauchsverhalten von Mauerwerk auf seine Robustheit geschlossen und wie der Schädigungsgrad im Erdbebenfall vorhergesagt und evaluiert werden kann.



1. INTRODUCTION

As for existing masonry structures, it is known that many of them are in illness state in their serviceability life time, slightly or seriously. In fact, suffering various unfavourable factors in construction and application, such as dispersity of masonry material, temperature cracks etc., masonry structures are in insufficient strength or strength deterioration state which is one of illness state concerned seriously. But the problem how to precisely examine the real serviceability state of masonry structures have not been solved for a long time. In this paper, method solving this problem was investigated, and the method developed from experimental information and theoretical analysis.

2. STRENGTH AND RIGIDITY

2.1 Compressive strength and rigidity

Compressive stress—strain curve of masonry envelope can be expressed [1][2]:

$$\sigma = f_m (1 - e^{-\alpha f_m^{1/2} \epsilon}) \quad (2-1)$$

where, σ and ϵ are compressive stress and strain respectively. f_m is the compressive strength of masonry envelope, α is a coefficient. Therefore, elastic modulus of masonry envelope can be obtained:

$$E = \left. \frac{d\sigma}{d\epsilon} \right|_{\epsilon=0} = \alpha f_m^{3/2} \quad (2-2)$$

Based on experimental information [1], the statistical value of α is 370. As we know, the (lateral) rigidity K is equal to the ratio of lateral load to displacement:

$$K = \frac{1}{\delta} = \frac{1}{\frac{h^3}{12EI} + \frac{h\xi}{GA}} = \frac{1}{\frac{h^3}{Etb^3} + \frac{1.2h}{0.3Etb}} = \frac{Et}{\left(\frac{h}{b}\right)^3 + 4\left(\frac{h}{b}\right)} \quad (2-3)$$

Substituting equation (2-2) into formula (2-3), the relation between rigidity and compressive strength can be got:

$$K = \frac{\alpha f_m^{3/2} t}{\left(\frac{h}{b}\right) \left[\left(\frac{h}{b}\right)^2 + 4 \right]} \quad (2-4)$$

in which, t , h and b are the thickness, height and width of masonry wall respectively.

2.2 Shear strength and rigidity

Researching the hysteresis characteristic of masonry wall [1][2][3], the statistical skeleton curve of hysteresis loops are shown in Figure 1, it is indicated that in the initial stage the load—displacement relationship is linear and after cracking the displacement increases significantly with appeared and developed cross cracks. Defined P_u as the ultimate load, Δu as the displacement in regard to p_u , and σ_c is the normal stress of masonry wall. The skeleton curve can be expressed as follow:

$$(1) P/P_u = 2.6 \frac{\Delta}{\Delta u} \quad (0 < P/P_u \leq 0.78, 0 < \frac{\Delta}{\Delta u} \leq 0.3) \quad (2-5)$$

$$(2) P/P_u = 0.69 + 0.31 \frac{\Delta}{\Delta u} \quad (0.78 < P/P_u \leq 1; 0.3 < \frac{\Delta}{\Delta u} \leq 1) \quad (2-6)$$

$$(3) P/P_u = 1 + 0.44(1 - 0.085\sigma_c) - 0.44(1 - 0.085\sigma_c) \frac{\Delta}{\Delta u} \quad (2-7)$$

$$(P/P_u < 1; 1 \leq \frac{\Delta}{\Delta u} \leq 0.3)$$

$$(4) P/P_u = 0.55 + 0.04\sigma_c \quad (2-8)$$

From formula (2-5), the rigidity K can be written as follow also:

$$K = \frac{P}{\Delta} = 2.6 \frac{P_u}{\Delta u} = 2.6 \frac{f_v t b}{\Delta u} \quad (2-9)$$

where, f_v is the shear strength of masonry wall. According statistical analysis, the relationship between f_v and Δu is:

$$\Delta u = (3 + 4.5f_v)^{1/2} / (0.45 + 0.05\sigma_c) \quad (2-10)$$

Thus,

$$K = \frac{(1.17 + 0.13\sigma_c) f_v t b}{(3 + 4.5f_v)^{1/2}} \quad (2-11)$$

Equation (2-11) illustrates the relationship between the rigidity K and the shear strength f_v .

2.3 Rigidity deterioration

Looking Fig. 1 again, it can be found that as increasing of displacement the stiffness of masonry wall decrease obviously. The stiffness K' at any displacement may be calculated from the following empirical formula:

$$K' = 0.0017(\Delta/H)^{-0.91} K \quad (\Delta/H > 1/1000) \quad (2-12)$$

In other word, formula (2-12) show the deterioration of rigidity as increasing of displacement Δ under later load.

3. ACCUMMLATED DEFORMATION ENERGY AND DAMAGE INDEX

3.1 Input energy of perunit mass

The problem related to the strength and stiffness of masonry wall in serviceability state are discussed above. In order to predict the damage degree of masonry structure, accumulated deformation energy should be stuided, because any damage by earthquake is the result of accumulated deformation in vabration process Assume that w is the accumulated deformation energy^[4,5]. As for one—freedom system, in general,

$$W = \frac{1}{2} m \dot{X}_{emaz}^2 \quad (3-1)$$

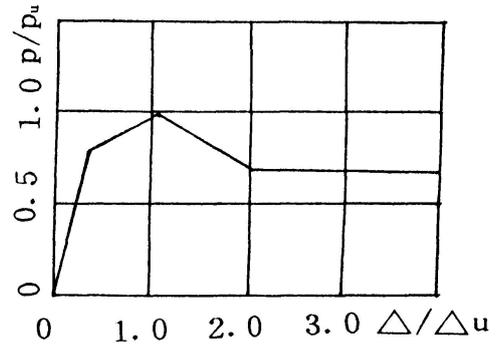


Fig. 1 Skeleton curve of masonry wall



where, \dot{X}_{emax} is the maximum value of elastic vibration velocity of system, and,

$$\dot{X}_{emax} = \dot{y}_{max} / 2^{1/2} \quad (3-2)$$

\dot{y}_{max} is the maximum velocity of earth's surface vibration. Substitute formula (3-2) into formula (3-1), then,

$$W = \frac{1}{4} m \dot{y}_{max}^2 = m E_0 \quad (3-4)$$

E_0 can be defined as the input energy of perunit mass. From statistical analysis, E_0 can be formulated as follow:

$$E_0 = \frac{1}{4} \dot{y}_{max}^2 = exp(1.385I - 6.39) \quad (3-5)$$

Where, I is the earthquake intensity.

3.2 Damage index of masonry structure

The vibration equilibrium equation of i th storey for multistorey masonry structures can be expressed (damp is neglected):

$$m_n \left(\sum_{j=1}^n \ddot{x}_j + \ddot{y} \right) + m_{n-1} \left(\sum_{j=1}^{n-1} \ddot{x}_j + \ddot{y} \right) + \dots + m_i \left(\sum_{j=1}^i \ddot{x}_j + \ddot{y} \right) = f_i(x_i) \quad (3-6)$$

Multiplying the equation by $\dot{x}_i dt = dx_i$, and integralling the equation in the whole vibration time, thus

$$\int \left(\sum_{k=1}^n m_k \sum_{j=1}^k \ddot{x}_j \right) dx_i + \int \dot{x}_i \sum_{k=i}^n m_k \ddot{y} dt = \int f_i(x_i) \dot{x}_i dt \quad (3-7)$$

It is noted that:

$$\int \ddot{x}_j dx_i = \int \ddot{x}_i dx_j = \int \dot{x}_j d\dot{x}_i = \int \dot{x}_i d\dot{x}_j = 0$$

$$\int \ddot{y} \dot{x}_i dt = \int \dot{x}_i d\dot{x}_i$$

$$x_i = h_i x_1 / h_1$$

therefore,

$$w_i = \int f_i(x_i) dx_i = \sum_{k=i}^n m_k \int \ddot{y} dx_i = \sum_{k=i}^n m_k \int \frac{h_i}{h_1} \dot{x}_1 d\dot{x}_i = \sum_{k=i}^n m_k \frac{h_i}{h_1} E_0 \quad (3-8)$$

h_i, h is the height of storey.

Assume that η_b and η are the ratio of ultimate deformation energy to elastic deformation energy and the ratio of deformation energy to elastic deformation energy respectively. According to experimental date, η_b is about 12 refer to masonry structures. η_b can be wrote as follow:

$$\eta_i = W_i/W_{iy} = 2 \sum_{k=i}^n m_k \frac{h_i}{h_1} E_0 / P_{\sigma} \Delta cr = 2K_r \sum_{k=i}^n m_k \frac{h_i}{h_1} E_0 / (\gamma f_v t b)^2 \quad (3-9)$$

γ is a statistical factor which is equal to 0.78. Let β express the damage index of masonry structures by earthquake, then,

$$\beta = \frac{W - W_y}{W_r - W_y} = \frac{\eta - 1}{\eta_r - 1} \quad (3-10)$$

From experimental and earthquake damage information [2, 3, 6], it can be defined that:

$\beta \geq 1.0$	<i>partly collapse</i>
$0.90 \leq \beta < 1.0$	<i>serious damage</i>
$0.50 \leq \beta < 0.90$	<i>moderate damage</i>
$0.15 \leq \beta < 0.50$	<i>slight damage</i>
$0 \leq \beta < 0.15$	<i>intact state</i>

4. APPLICATION

4.1 Application

Up to now, we discussed the strength, rigidity and accumulated deformation energy. In this section, we will discuss how to evaluate the strength of masonry structures in service. Serviceability state and how to predict the damage of masonry structure by earthquake. As we know that structure's natural frequency and mode of vibration can be measured and analyzed from ambient vibration. So the rigidity of structures can be identified using the data of natural frequency, mode of vibration and equilibrium equation of vibration. Since the rigidity can be identified, substituting the rigidity into formulae (2-4) and (2-11). Using formulae (2-1) and (2-3), the compressive and shear strength of masonry structures can be evaluated. On the basis of these results, it can be found that which storey is the weak part in serviceability state or under earthquake circumstance. Applying (3-9) and (3-10), it can be predicted that which degree of damage will be caused under great earthquake intensity.

4.2 Example

A multistorey masonry structure. Seven storey, the height of storey is 2800mm. its plane figure referring to Fig2. The thickness of outer horizontal wall is 490mm, inner horizontal wall are 370mm (the first floor) and 240mm (from the second to the seventh). The thickness of outer transverse wall is 370mm. The results of measured data from ambient vibration are shown in table 1. Using the data of table 1 and the method discussed above. The distribution of rigidity, strength and damage index under seven degree of earthquake intensity etc are calculated and shown in table 2.



Table 1. The results of ambient vibration

Floor	weight(kg)	Ai(mm)	K _i (KN/m)
1	6.928×10^5	0.019	8.75×10^6
2	6.566×10^5	0.038	8.53×10^6
3	6.566×10^5	0.061	6.74×10^6
4	6.566×10^5	0.16	1.42×10^6
5	6.566×10^5	0.18	55.43×10^6
6	6.566×10^5	0.20	33.50×10^6
7	4.156×10^5	0.26	1.49×10^6
note	frenquence $f_1=2.832\text{HZ}$		

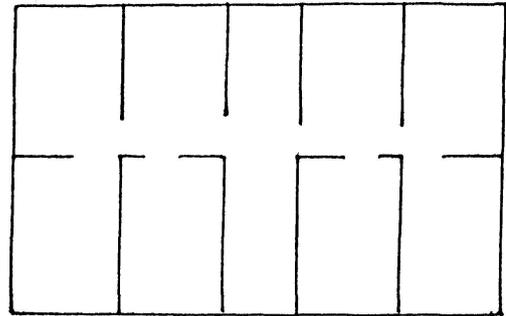


Fig. 2 Plane figure of example

Table 2 The results of evaluation

Floor	K _i (KN/m)	Compressive strength (MP _a)	shear strength (MP _a)	compressive stress (MP _a)	earthquake shear stress	Damage index
1	8.75×10^6	2.80	0.47	0.47	0.15	0
2	8.53×10^6	3.62	0.599	0.55	0.29	0.44
3	6.74×10^6	3.10	0.440	0.46	0.26	0.13
4	1.42×10^6	1.10	0.076	0.36	0.23	7.10
5	5.43×10^6	2.68	0.332	0.27	0.18	0.20
6	3.50×10^6	2.00	0.200	0.19	0.122	0.30
7	1.44×10^6	1.13	0.092	0.09	0.05	0.26

note: 1. earthquake intensity is seven degree.
 2. earthquake shear stress caculated by equivalent base shear method.

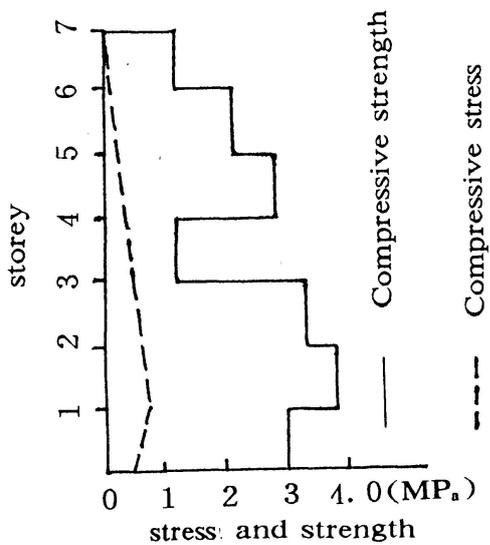


Fig. 3 Distribution of compressive strength and stress

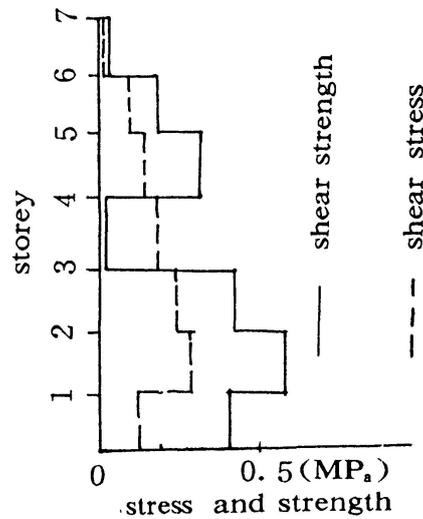


Fig. 4 Distribution of shear strength and stress

6. CONCLUSION AND DISCUSSION

- ① Above, the strength, the rigidity, the deformation energy and the damage index of masonry structure are studied. Relationship between them are given also.
- ② Using the relationship and data from ambient vibration, the serviceability state of existing masonry structures can be asserted, and the damage index by earthquake can be predict also.
- ③ Based on experimental statistical information and structural dynamic analysis. The method reflect every aspect involved in masonry structure and suggest a way to examine the existing masonry structure comprehensively.
- ④ Example show that the compressive strength, the shear strength and the damage index evaluated by the method are in good agreement.
- ⑤ Examples show that the method are feasible. The assertment results of existing masonry structure are reliability.
- ⑥ Further investigation should be carried and make the method more perfecter.

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