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Research Article

Importance Assessment of Structural Members Based on Elastic-Plastic Strain Energy

Yongjun Lin,[1] **Xianzhao Zhang**,[1] **Wenqiang Xu**,[1] **and Meng Zhou**[2]

[1]*School of Civil Engineering, Southwest Jiaotong University, Chengdu 610031, China*
[2]*China Southwest Architectural Design and Research Institute Corp. Ltd., Chengdu 610041, China*

Correspondence should be addressed to Yongjun Lin; scsmith@126.com

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Based on the elastic analysis, the existing methods of the importance assessment of structural members can only reflect the structural elastic behavior. To understand the plasticity and stiffness degradation of the structure, the present study proposes a member importance assessment method which takes the structural elastic-plastic strain energy or the generalized elastic-plastic strain energy as the performance parameter. First, the existing methods of member importance assessment are explained. Second, by pushover analysis, structural elastic-plastic strain energy is calculated in accordance with the story force-displacement curve, and structural generalized elastic-plastic strain energy is calculated according to the base shear-top displacement curve. Third, the importance of structural members is measured with its effect on the elastic-plastic strain energy or generalized elastic-plastic strain energy of the structure. Given the difference between structural performance parameters, the coefficient of member importance is defined. Finally, the importance of the masonry structure wall is quantitatively assessed using the elastic-plastic strain energy method, the generalized elastic-plastic strain energy method, the generalized stiffness method, and the ultimate bearing capacity method. Besides, the effect of the seismic fortification intensity and the number of structural stories on the wall importance assessment results is analyzed. According to the results, the elastic-plastic strain energy method and the generalized elastic-plastic strain energy method can both reveal the mechanical performance of elastic-plastic state of the structure under severe earthquake. Furthermore, the greater the seismic fortification intensity is, the more important the wall will be on the bottom floor, the more the total number of structural stories will be, and the more important the opening wall and its adjacent wall will be.

1. Introduction

Most structures are composed by different elements in various ways. In general, the structural capacity to resist the given loads refers to a function of the capacity of the individual element [1]. Besides, the applications of modern design codes to the design of realistic structures are primarily suitable for a member level [2, 3]. It is obvious that the damage or failure of individual members may not directly cause the structural collapse or the complete loss of system functionality. Key members will impact the overall performance of the structure more significantly and should be paid more attention to in structural design and service life. Accordingly, understanding the importance of different members in structural systems is of huge significance, which should also suggest the extent to which members affect the performance of structural system.

In general, the assessment methods of member importance can fall into qualitative assessment and quantitative assessment. Though the implementation of qualitative assessment is relatively simple, it relies on the experience of engineers, and it is generally applicable to simple structures only [4]. For this reason, many researchers have developed member importance assessment methods based on the quantitative analysis. Reliability-based methods of assessing the safety and the performance of existing structures and infrastructure systems have been widely accepted [5]. By system reliability analysis, the member importance can be measured with the degree of structural reliability reduction caused by the resistance decrease of structural members [6, 7]. Due to the complexity of the structural members, considerable computation is required to calculate system reliability, which is not suitable for actual engineering. To develop a convenient method for assessing the member importance, Zhang et al. [8] established the energy flow network of the frame structure under the conservative system in accordance with the theory of energy transfer. The member importance is determined by the effect of the removed member on the total strain energy of the structure. However, this method can only be used for structures under elastic conditions, and the effect of dynamic action on the structure is also not considered. The published literature includes numerous papers on the member importance assessment based on the conception of structural stiffness. Liu et al. [9] reported that the member importance is directly proportional to the member elastic stiffness. A unit force system (e.g., axial force, shear force, and bending moment) was introduced in the main directions of member stiffness, and the total internal forces in each direction were selected as the importance index of the member. However, no solid theoretical basis was laid for the simple addition of different internal forces as the member importance index. The rationality of such method is debatable. Nafday [10] obtained the stiffness matrix determinant of the structure and standardized it using alternative load path (ALP) methods. The ratio of the stiffness matrix determinant between the intact structure and the structure of removed members can be obtained. Nevertheless, this index is less important physically. It is difficult to reflect the importance of structural members in engineering. Researchers from the University of Bristol [11–13] applied topology and graph theory to the robust analysis of structures, which are viewed as the combination of rings and clusters. By identifying the formation and failure modes of structural rings and clusters, the damage index is proposed based on the structural stiffness matrix. Since the physical meaning of the index is unclear, problem still remains. In addition, these stiffness-based member importance assessment methods have ignored the effect of different load transfer path on the member importance in the structural system. Considering that structural performance is more susceptible to the member with more contribution to load transfer, an index, generalized stiffness, is proposed by Ye et al. [4], and the effect of the demolished member on generalized structural stiffness is taken as the member importance assessment index. The physical conception of this index is clear, but only limited to the elastic structural system. Frequently, nonlinear static analysis (pushover analysis) is one of the most suitable tools for structural seismic assessment. Structural ultimate base shear can be obtained by pushover analysis. Assessing the member importance by the influence degree of structural members on structural ultimate base shear, Yang [14] defines the member importance assessment index based on ultimate bearing capacity. But this index does not reflect the mechanical behavior of the structure from reaching the ultimate shear to the collapse stage and stiffness degradation characteristics of the structure under severe earthquake.

A structure is only elastic under moderate earthquakes. When the structure is subjected to severe earthquakes, it should be allowed to be plastic, which also meets current seismic specifications. Hence, member importance assessment based on elastic analysis is appropriate for the structure under small earthquakes. For structures under large earthquakes, the valid member importance assessment method should perform elastic-plastic analysis and reflect stiffness degradation characteristic of the structure. Pushover analysis can fully reflect the local plastic deformation and the overall deformation mechanism of the structure while does not require excessive computational time [15–17]. Thus, pushover analysis is applied to the member importance assessment method proposed in this study which establishes a new member importance assessment method. By pushover analysis, structural elastic-plastic strain energy is calculated according to the story force-displacement curve and structural generalized elastic-plastic strain energy is calculated according to the base shear-roof displacement curve. Moreover, the importance of structural members is reflected by its effect on the elastic-plastic strain energy or generalized elastic-plastic strain energy of the structure. This importance assessment method of structural members can be called the elastic-plastic strain energy method or generalized elastic-plastic strain energy method. Finally, to understand the effect of the seismic fortification intensity and the number of structural stories on the wall importance assessment, the masonry wall of example structures is quantitatively assessed using the elastic-plastic strain energy method.

2. Existing Calculation Methods

From the analysis method, the importance assessment of structural members can be divided into elastic analysis and elastic-plastic analysis, and the former is the majority. In terms of elastic analysis, the generalized stiffness method is the most representative, while the elastic-plastic analysis primarily includes the ultimate bearing capacity method. Due to space limitations, this study only introduces the generalized stiffness method and the ultimate bearing capacity method.

2.1. Generalized Stiffness Method. The generalized stiffness method takes the influence degree of the member on the general structural stiffness as the importance assessment index of the structural member. The generalized structural stiffness here is based on linear elastic analysis. The load distribution is defined as the generalized force F_{stru} and the resulting displacement distribution is defined as the generalized displacement D_{stru}. Thus, the generalized structural stiffness can be calculated as follows [4]:

$$K_{\text{stru}} = \frac{F_{\text{stru}}}{D_{\text{stru}}}, \tag{1}$$

where K_{stru} denotes the general structural stiffness.

The impact of the member on the generalized structure stiffness can be obtained using the alternative load path method. First, a certain member of the structure is removed to yield a new structure. Subsequently, the generalized structural stiffness is yielded by linear elastic analysis. Finally, the generalized structural stiffness of the removed member is compared with that of the intact structure, and the importance assessment indicator of this removed member is computed as

$$I_{j,\mathrm{gs}} = 1 - \frac{K_{\mathrm{stru},j}}{K_{\mathrm{stru},0}}, \quad j = 1, 2, \ldots, n, \tag{2}$$

where $I_{j,\mathrm{gs}}$ denotes the j-th member importance assessment index based on generalized stiffness; $K_{\mathrm{stru},j}$ is the general structural stiffness after the removal of the j-th member; $K_{\mathrm{stru},0}$ is the generalized structural stiffness of the intact structure; and n is the total number of structure members.

This method is based on linear elastic analysis, but the results of member importance assessment can only reflect the elastic performance of the structure.

2.2. Ultimate Bearing Capacity Method. The ultimate bearing capacity method takes the influence degree of the member on the ultimate base shear of the structure as the importance assessment index of the structural member. First, a new structure is obtained from removing a certain member of the structure. Then, the ultimate base shear is obtained from pushover analysis. Finally, the importance assessment index of this removed member can be deduced from the relationship between the ultimate base shear after the member is removed and the ultimate base shear of the intact structure [14]:

$$I_{j,\mathrm{ubc}} = 1 - \frac{V_{\mathrm{stru},j}}{V_{\mathrm{stru},0}}, \quad j = 1, 2, \ldots, n, \tag{3}$$

where $\mathrm{I}_{j,\mathrm{ubc}}$ denotes the j-th member importance assessment index based on the ultimate bearing capacity; $V_{\mathrm{stru},j}$ is the ultimate base shear after removing the j-th member; and $V_{\mathrm{stru},0}$ is the ultimate base shear of the intact structure.

This method is based on pushover analysis, and the importance of structural members is measured by the effect of structural members on the ultimate base shear. However, using this method, it cannot reflect the mechanical behavior from the ultimate shear to the collapse stage and the stiffness degradation characteristics of the structure under severe earthquakes.

3. Proposed Methods

Based on elastic analysis, the generalized stiffness method can only reflect the elastic performance of the structure. Also, based on static elastic-plastic analysis, the ultimate bearing capacity method fails to exhibit the mechanical behavior of the structure from reaching the ultimate base shear to the collapse stage. Thus, this study proposes a new method of the member importance assessment, in which structural elastic-plastic strain energy or generalized elastic-plastic strain energy is viewed as performance parameters of the member importance assessment.

For this method, the structural elastic-plastic strain energy is calculated by pushover analysis according to the story force-displacement curve. Besides, the structural generalized elastic-plastic strain energy of the structure is computed in line with the base shear-roof displacement curve.

Moreover, the importance of structural members is measured with its effect on the elastic-plastic strain energy or generalized elastic-plastic strain energy of the structure. This importance assessment method of structural members can be named as the elastic-plastic strain energy method or generalized elastic-plastic strain energy method. In this study, the elastic-plastic strain energy method and the generalized elastic-plastic strain energy method will be introduced separately.

3.1. Elastic-Plastic Strain Energy Method. In the pushover analysis, it is assumed that the seismic response of the structure is controlled only by the fundamental mode and the shape vector remains unchanged under horizontal seismic action. By applying lateral forces monotonically in a step-by-step static analysis on the structure (Figure 1(a)), the members are sequentially brought into a plastic state until the entire structure reaches the target displacement or collapse [18]. Pushover analysis can not only consider the plastic behavior of the structure but also reflect the mechanical performance during the whole process. Among them, the target (ultimate) displacement can be determined from the failure state of the structure which can be defined as the lateral shift of the top control point when the ultimate base shear of the structure is reduced to 85%. And this point serves as the collapse control point of the structure [16].

By pushover analysis for the structure, the lateral force-floor displacement curve can be obtained (Figure 1(b)), and also the base shear-roof displacement (V-u) curve of the structure can be plotted (Figure 1(c)). The work done by the lateral force on the structure can be construed graphically as the area beneath the curve of lateral force-floor displacement obtained from the pushover analysis (shaded portion shown in Figure 1(b)). The total work by the lateral force of all floors on the structure is the work done by the lateral force (external load) on the structure. It can also be understood as the energy required to collapse the structure, i.e., the elastic-plastic strain energy of the structure.

The formula to calculate the work done by the floor lateral force on the structure is expressed as

$$E_{i,j} = \int_0^{u_{i,j,\mathrm{col}}} F_{i,j} d_{u_{i,j}}, \quad i = 0, 1, 2, \ldots, m, \; j = 0, 1, 2, \ldots, n, \tag{4}$$

where $F_{i,j}$ denotes the lateral force of the i-th floor of the structure after the j-th member is removed; $u_{i,j}$ is the displacement of the i-th floor after the j-th member is removed; $u_{i,j,\mathrm{col}}$ is the displacement of the i-th floor when the structure is collapsed after the j-th member is removed; $E_{i,j}$ refers to the work done by the lateral force of i-th floor after the j-th member is removed; m is the total number of structural floors; and n is the total number of structural

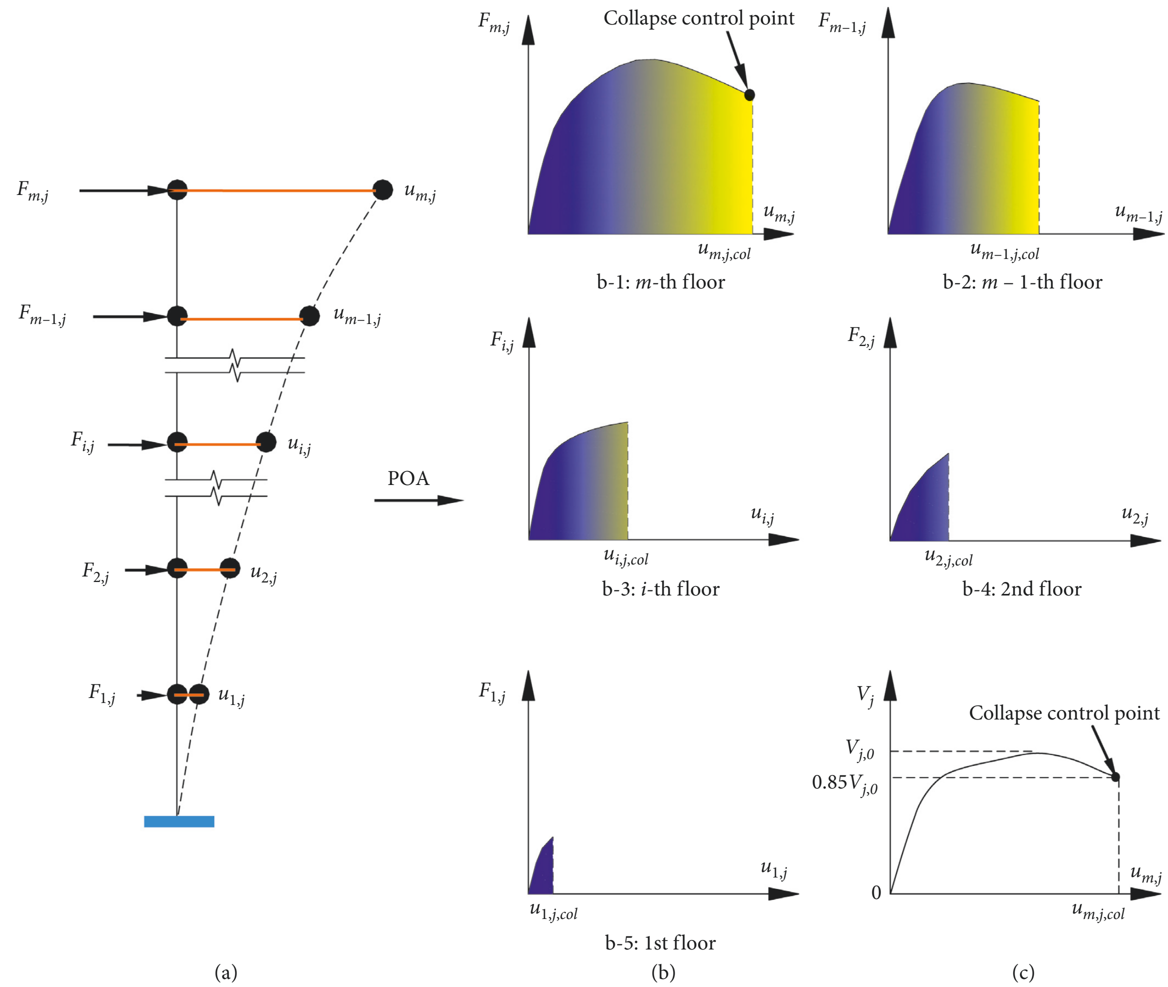


FIGURE 1: Structural elastic-plastic strain energy based on pushover analysis. (a) Pushover analysis model. (b) Lateral force-floor displacement curve. (c) Bottom shear-top lateral displacement curve.

members. When the subscript $j = 0$, the structure is indicated to be intact.

The energy that should be inputted to collapse the structure can be expressed by the total work by the lateral force of all floors:

$$U_j = \sum_{i=1}^{m} E_{i,j}, \quad j = 0, 1, 2, \ldots, n, \tag{5}$$

where U_j denotes the energy (the elastic-plastic strain energy of the structure) required to input to collapse the structure after the removal of the j-th member.

According to the definition of member importance, the importance assessment index of member based on elastic-plastic strain energy is expressed as

$$I_{j,\text{epde}} = \frac{U_0 - U_j}{U_0} = 1 - \frac{U_j}{U_0}, \quad j = 0, 1, 2, \ldots, n, \tag{6}$$

where $I_{j,\text{epde}}$ denotes the importance assessment index of the j-th member based on the structural elastic-plastic strain energy.

Based on the pushover analysis, this method assesses the importance of the member by structural elastic-plastic strain energy, which can reflect the mechanical performance of elastic-plastic state of the structure under severe earthquake.

3.2. Generalized Elastic-Plastic Strain Energy Method. There are also shortcomings to assess importance of structural members based on elastic-plastic strain energy. It requires considerable computational effort to calculate the elastic-plastic strain energy of the structure according to the lateral force-floor displacement curve of each floor.

Accordingly, the concept of generalized elastic-plastic strain energy of the structure is introduced here. The generalized elastic-plastic strain energy is defined as the work done by the base shear on the roof displacement of the structure. The base shear-roof displacement curve of the structure (Figure 1(c)) obtained by pushover analysis can be used to calculate the generalized elastic-plastic strain energy:

$$U_{j,\text{ge}} = \int_0^{u_{m,j,\text{col}}} u_{m,j} V_j du_{m,j}, \tag{7}$$

where $U_{j,\mathrm{ge}}$ denotes the generalized elastic-plastic strain energy of the structure after the j-th member is removed.

Based on the generalized elastic-plastic strain energy, the importance assessment index of structural members can be represented as

$$I_{j,\mathrm{ge}} = \frac{U_{0,\mathrm{ge}} - U_{j,\mathrm{ge}}}{U_{0,\mathrm{ge}}} = 1 - \frac{U_{j,\mathrm{ge}}}{U_{0,\mathrm{ge}}}, \quad j = 0, 1, 2, \ldots, n, \tag{8}$$

where $I_{j,\mathrm{ge}}$ denotes the importance assessment index of the j-th member based on generalized elastic-plastic strain energy.

It is noteworthy that though the importance calculation of structural members based on generalized elastic-plastic strain energy is relatively simple, it does not have a clear physical meaning as the elastic-plastic strain energy method does.

In particular, for a single-story structure, the importance calculation results obtained using the elastic-plastic strain energy method are the same as those using the generalized elastic-plastic strain energy method. The more floors of the structure, the greater the difference between these two methods. For the importance assessment of structural members with more floors, the generalized elastic-plastic strain energy method should not be used.

4. Importance Coefficient of Structural Members

The building structure is an extremely complex engineering system, and different structural performance parameters can measure the different mechanical behavior of the structure. The importance assessment index of structural members obtained by different structural performance parameters only represents the influence degree of a certain member on the performance of a particular structural performance. Thus, the same structural member may get different importance assessment index based on different structural performance parameters. In fact, in the same structure, the member importance is also relative.

To eliminate the effect of different methods or different performance parameters on the importance assessment of members, it is more reasonable to standardize the importance assessment index of members. As a result, in this study, the weight factor of the importance assessment index of members is defined as the importance coefficient of structural members, and its calculation formula is

$$\gamma_j = \frac{I_j}{\sum_{j=1}^{n} I_j}, \tag{9}$$

where γ_j is the importance coefficient of the $j-$th member and I_j is the importance assessment index of the $j-$th member, which can be obtained using the generalized stiffness method, the ultimate bearing capacity method, the elastic-plastic strain energy method, and the generalized elastic-plastic strain energy method.

5. Importance Assessment of Walls of Multistory Masonry Structures

The wall importance of multistory masonry structures is assessed by the existing methods (generalized stiffness method and ultimate bearing capacity method) and the proposed methods (the elastic-plastic strain energy method and generalized elastic-plastic strain energy method), respectively.

5.1. Modeling Strategy. According to the current provisions of the standard (GB50011-2010) [19], three masonry structure models were designed here. There are 2 three-story masonry structures and one four-story masonry structure. Model design parameters are listed in Table 1. In particular, the MAS in MASa-b(c) exhibits the masonry structure, a indicates the number of structural stories, b shows the seismic fortification intensity, and c denotes the design ground motion parameter.

All example models have the same plane layout. The opening dimensions of the wall are 860 mm × 2050 mm, 1500 mm × 2050 mm, and 1200 mm × 1500 m. The story height is 3.0 m, and the slab thickness is 100 mm. Each floor is provided with a ring beam of 240 mm × 180 mm and the structural column of 240 mm × 240 mm. The layout of the three-story structure is shown in Figure 2. The four-story structure is similar to the three-story structure and not explained here.

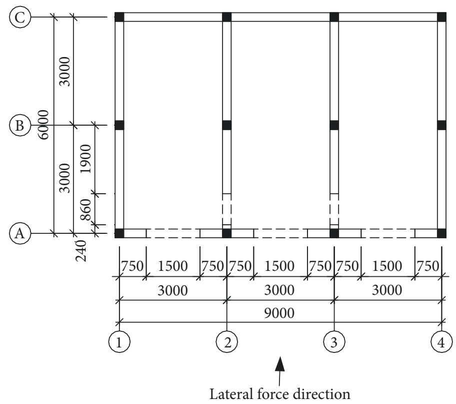
Fired common bricks and mixed mortar were used for the construction of masonry walls. The floor slabs were cast-in-place. For ring beams, structural columns, and slabs, the properties of concrete were $f_c' = 14.30\,\mathrm{N/mm^2}$ and $E_c = 3.00 \times 10^4\,\mathrm{N/mm^2}$. Also, for longitudinal reinforcements and stirrups, the properties of reinforcing steel were $f_c = 360\,\mathrm{N/mm^2}$ and $E_c = 2.00 \times 10^5\,\mathrm{N/mm^2}$. The live load on the floor is $2.00\,\mathrm{kN/m^2}$ and on the roof is $0.50\,\mathrm{kN/m^2}$.

5.2. Pushover Analysis. Structural finite element modeling and pushover nonlinear analysis are performed using nonlinear mechanical analysis software ABAQUS. The structural column, ring beam, slab, and masonry wall are overall composed of eight-node hexahedral element C3D8R, and the steel bar adopts T3D2 unit. Since the slab and ring beam are considered to be cast-in-place, the slab and the ring beam are merged into Part during modeling, and the Tie command is employed to constrain the structural column and the wall, the ring beam, and the wall. The command can make the two contact with each other. The surface is continuously displaced, yet the stress is not necessarily continuous, and the actual force characteristics of the masonry structure can be reasonably suggested. The surface contact between the ring beam and the masonry is simulated via the Surface-to-Surface Contact. The sliding friction coefficient μ between the ring beam and the masonry reaches 0.7 [20].

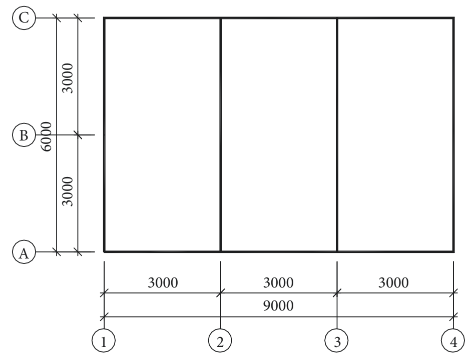
The constitutive model of concrete complies with the uniaxial compression (tension) stress-strain relationship of concrete given in the standard (GB50010-2010) [21]. The ideal elastic-plastic constitutive model of rebar is employed.

Table 1: Overview of model design parameters.

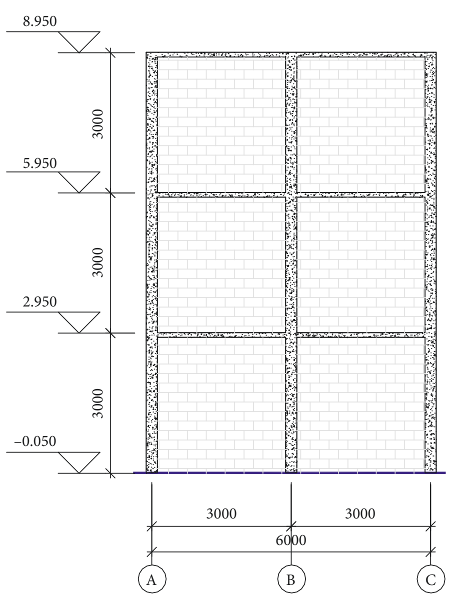
Series	Example structure ID	Total number of stories	Seismic fortification intensity (design ground motion parameter)	Wall thickness (mm)	Strength grade of block/mortar
1	MAS3-7 (0.1 g)	3	7 (0.1 g)	240	MU10/M5
2	MAS4-7 (0.1 g)	4	7 (0.1 g)	240	MU10/M5
3	MAS3-8 (0.2 g)	4	8 (0.2 g)	240	MU15/M7.5



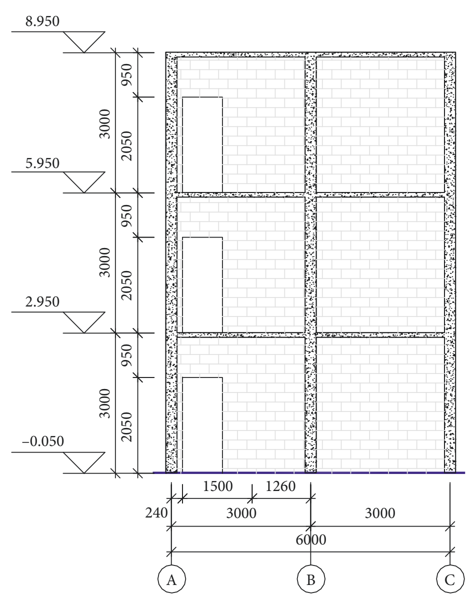
(a)



(b)

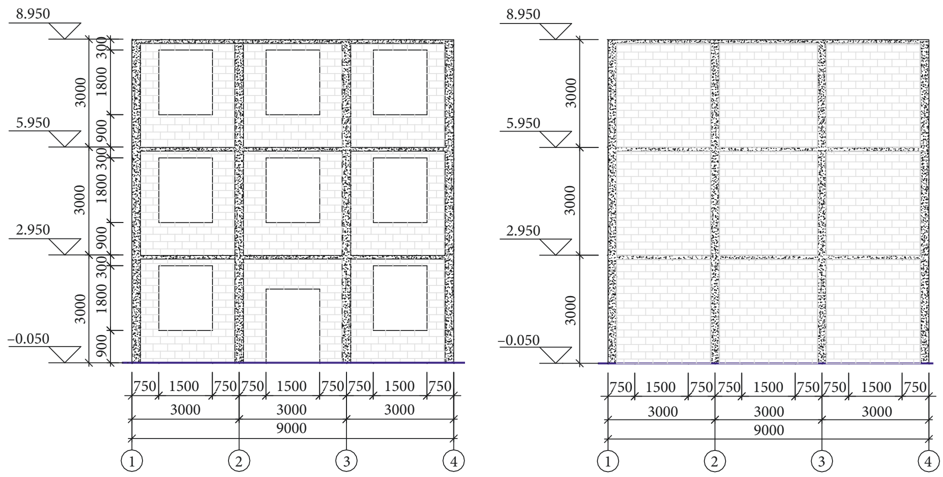


(c)



(d)

Figure 2: Continued.



(e) (f)

Figure 2: Layout of the three-layer masonry example structure (unit: m, mm). (a) Plane layout. (b) Ring beam layout. (c) Façade of ①/④ axes. (d) Façade of ②/③ axes. (e) Façade of Ⓐ axis. (f) Façade of Ⓒ axis.

The plastic damage constitutive model is adopted for masonry, and its elastic modulus E and compressive yield strain $\varepsilon_{\mathrm{cm}}$ are calculated by equations (10) and (11), respectively [22]:

$$\varepsilon_{\mathrm{cm}} = \frac{0.005}{\sqrt{f_{\mathrm{cm}}}}, \tag{10}$$

$$E = 370 f_{\mathrm{cm}}^{3/2}, \tag{11}$$

where f_{cm} denotes the average value of the masonry compressive strength (unit: MPa).The constitutive relationship curve of masonry compression plastic damage is shown in Figure 3.

For the pushover analysis, the lateral forces are stretched along the lateral direction of the structure (Figure 2(a)), and the distribution pattern is the inverted triangles along the vertical direction of the structure (Figure 1(a)).First, the intact structure is analyzed. Subsequently, the new structure is formed by the layer-by-layer displacement curve and the horizontal removal of the wall, the pushover analysis is conducted, and the bottom shear-top lateral force-lateral displacement curve of the floor is plotted.

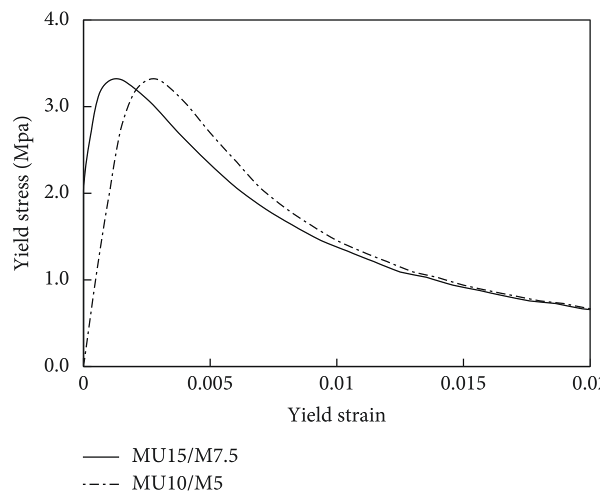


Figure 3: Constitutive relationship curve of masonry compression plasticity damage.

5.2.1. Base Shear-Roof Displacement Curve. The bottom shear-top lateral displacement curve of the example structure and the layer-by-layer removal of the wall structure are plotted in Figure 4. The intact structure in the figure represents the original structure; “Dem $i|m\&n$/A-B” means to remove the structure of the wall between the A and B axes of the i – th layer m or the n-axis; i is the number of layers; $m\&n$ is the m-axis or the n-axis; A-B is the A-axis to the B-axis. For instance, “Dem 1|1&4/B-C” means to remove the structure of the wall between the B and C axes on the 1st or 4th axis of the first layer.

This figure shows that in the elastic stage, the wall has slight effect on the structural stiffness. The bottom shear-top lateral displacement curve of the intact structure is very close to the structure of the demolished wall; when the structure is formed, it enters the elastoplasticity. Then, the bottom shear-top lateral displacement curve of the demolition wall structure is significantly lower than that of the intact structure, suggesting that the effect of the wall on the structural stress performance during the elastoplastic phase is greater than that of the elastic phase. Accordingly, the assessment of the importance of components using elastic analysis does not reflect the effect of components on the plastic properties of the structure [4].

5.2.2. Story Force-Displacement Curve. The horizontal force-lateral displacement curve of the structural floor is shown in Figures 5–7. These figures show that when the control point is moved laterally to the side of the collapse control point, the lateral displacement of the top of the structure becomes the

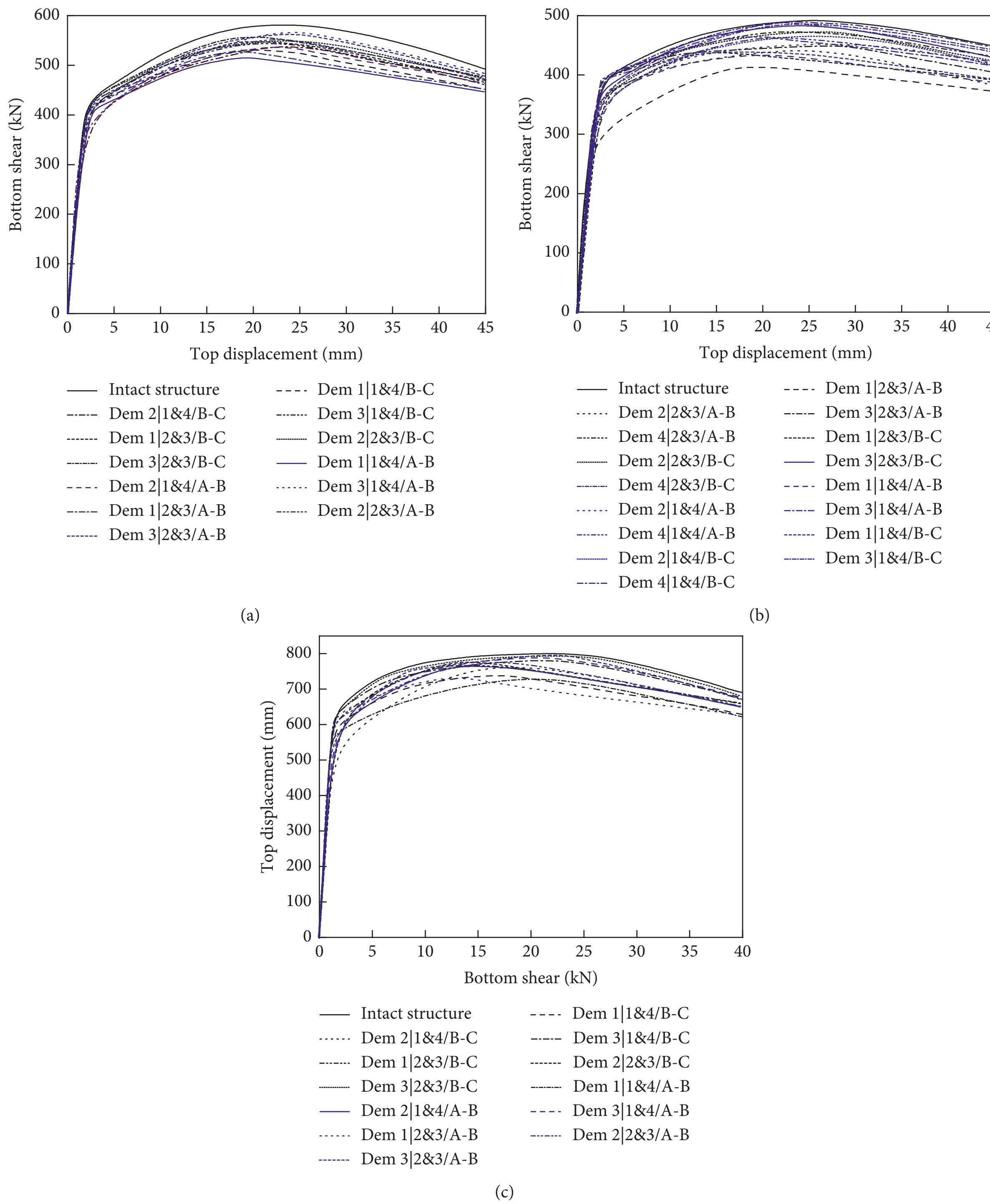


Figure 4: Bottom shear-top displacement curve. (a) Model: MAS3-7 (0.1 g). (b) Model:MAS4-7 (0.1 g). (c) Model:MAS3-8 (0.2 g).

largest, and the lower the number of layers is, the smaller the lateral displacement will be; due to the lower strength of the masonry structure, the structure of each floor before the collapse also enters the plastic stage.

5.3. Importance Assessment of the Wall. First, according to the lateral force-floor displacement curve, the importance assessment index of the wall based on elastic-plastic strain energy is calculated using equations (4)–(6). Second, according to the base shear-roof displacement curve, the importance assessment index of the wall based on generalized elastic-plastic strain energy is calculated using equations (7) and (8). Third, based on generalized stiffness method and ultimate bearing capacity method, the importance assessment index of the wall is calculated, respectively,

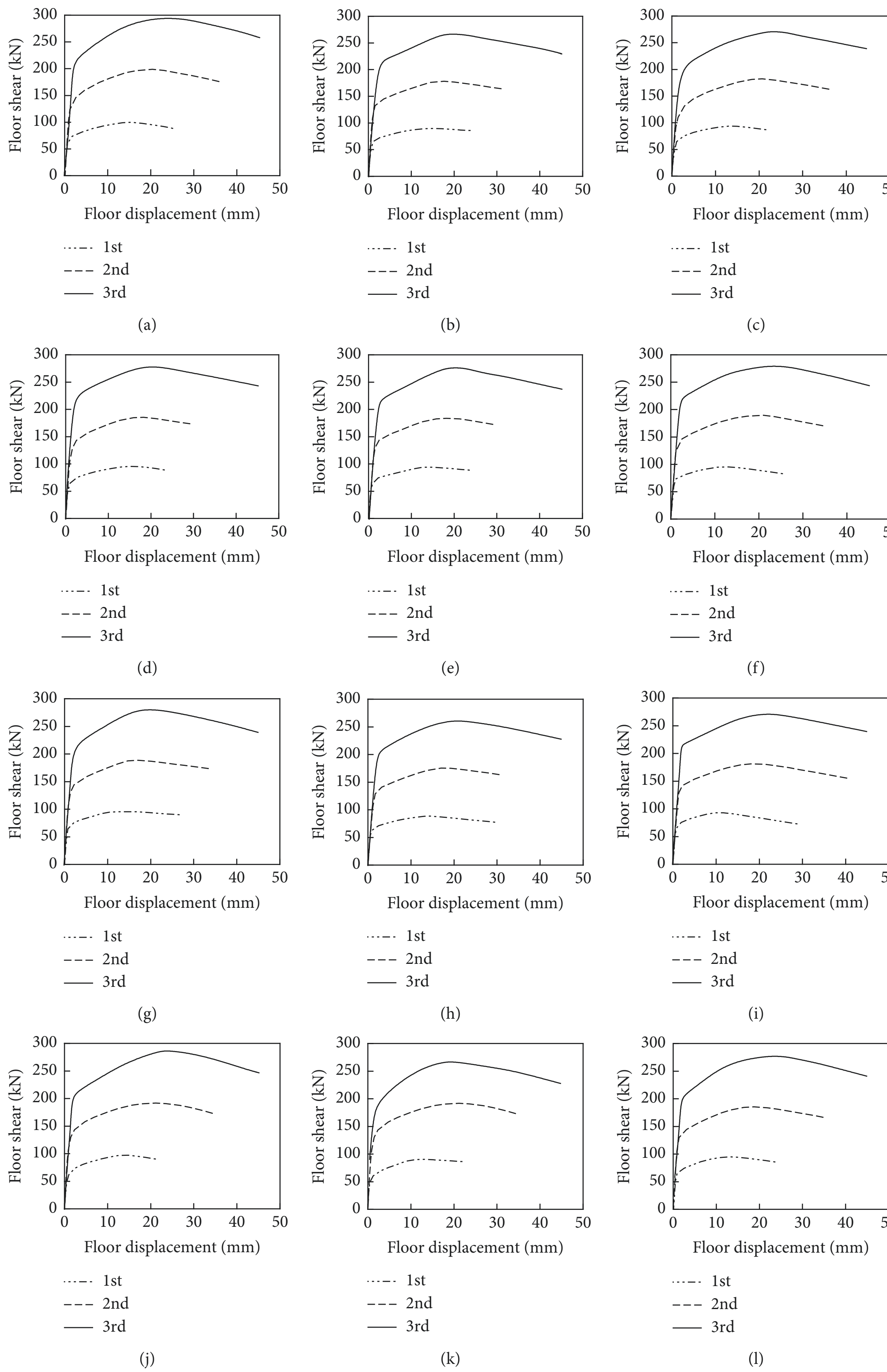
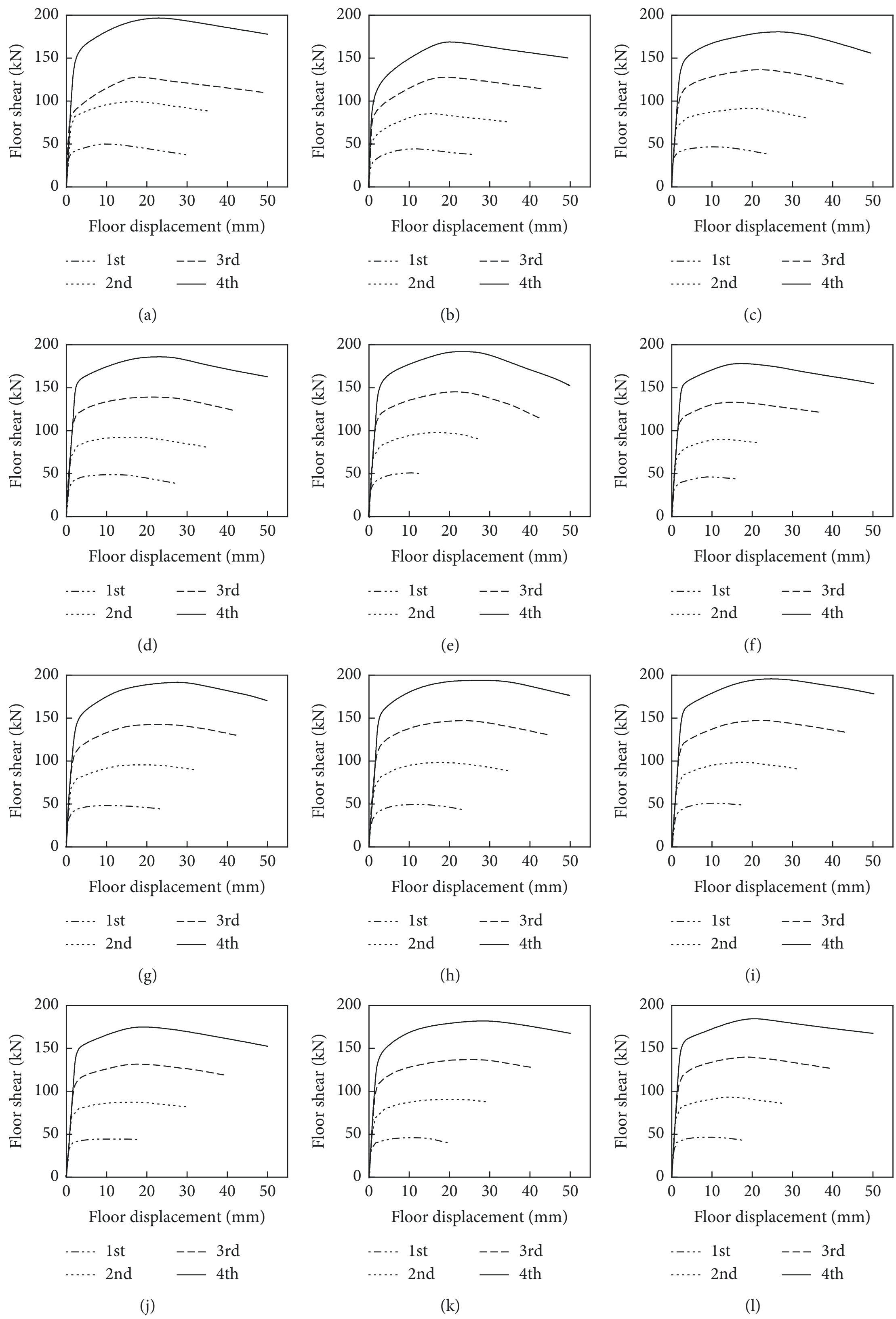


Figure 5: Horizontal floor force-lateral displacement curve <Model MaS3-7 (0.1 g)>. (a) Intact structure model. (b) Dem 1|1&4/B-C. (c) Dem 2|1&4/B-C. (d) Dem 3|1&4/B-C. (e) Dem 1|2&3/B-C. (f) Dem 2|2&3/B-C. (g) Dem 3|2&3/B-C. (h) Dem 1|1&4/A-B. (i) Dem 2|1&4/A-B. (j) Dem 3|1&4/A-B. (k) Dem 1|2&3/A-B. (l) Dem 2|2&3/A-B.



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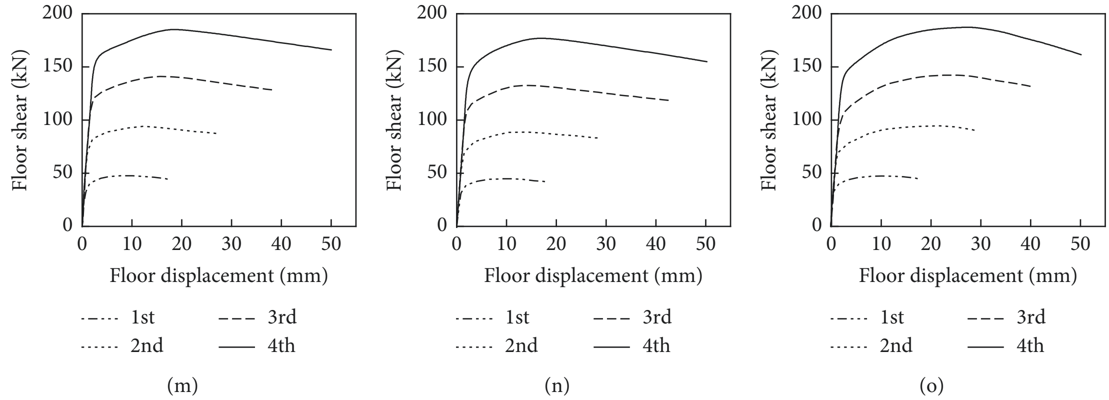

Figure 6: Horizontal floor force-lateral displacement curve <MaS4-7 (0.1 g)>. (a) Intact structure model. (b) Dem 1|2&3/A-B. (c) Dem 2|2&3/B-C. (d) Dem 3|2&3/A-B. (e) Dem 4|2&3/A-B. (f) Dem 1|2&3/B-C. (g) Dem 2|2&3/B-C. (h) Dem 3|2&3/B-C. (i) Dem 4|2&3/B-C. (j) Dem 1|1&4/A-B. (k) Dem 2|1&4/A-B. (l) Dem 3|1&4/A-B. (m) Dem 4|1&4/A-B. (n) Dem 1|1&4/B-C. (o) Dem 2|1&4/B-C.

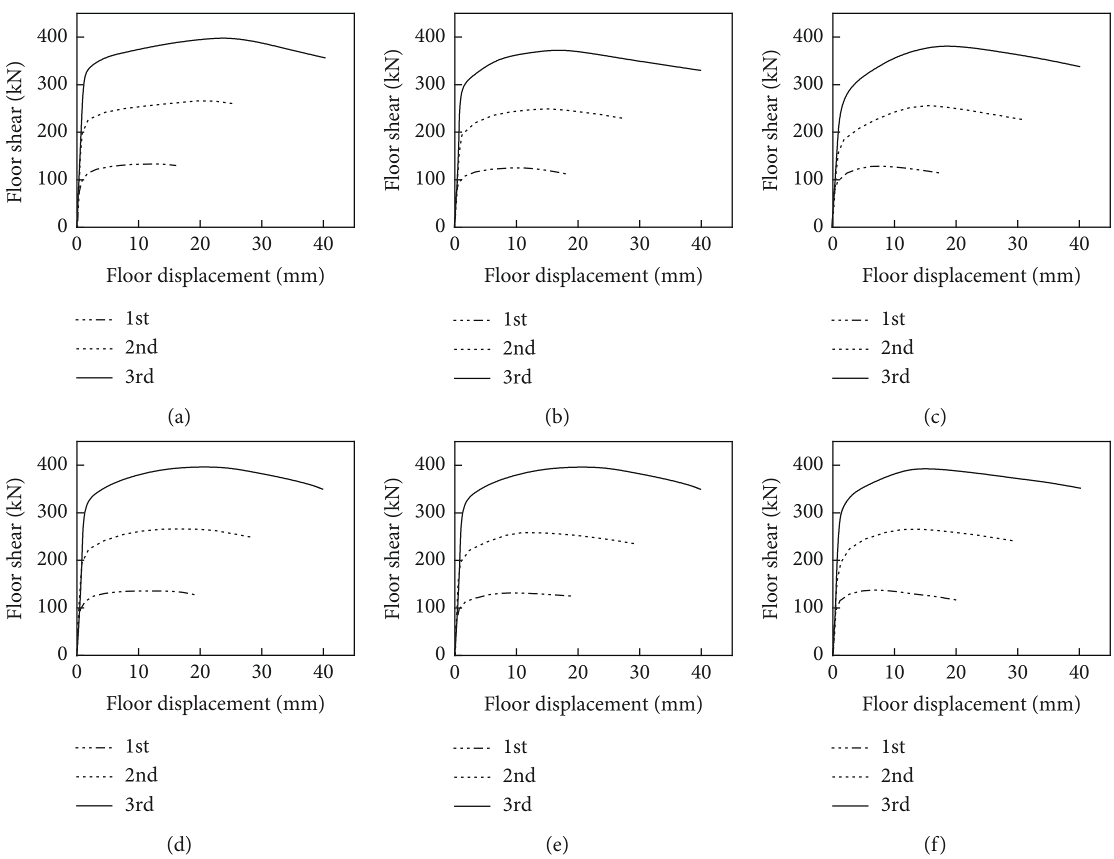

Figure 7: Continued.

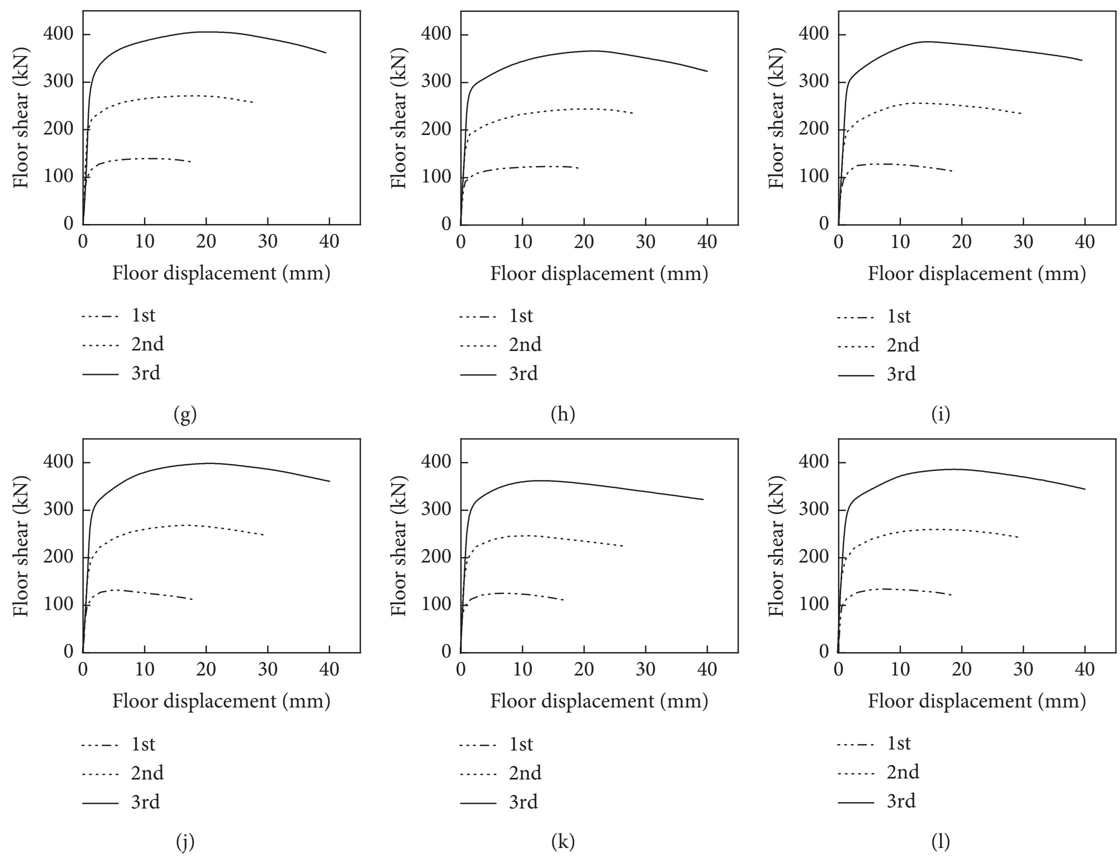

Figure 7: Horizontal floor force-lateral displacement curve < MaS3-8 (0.2 g)>. (a) Intact structure model. (b) Dem 1|1&4/B-C. (c) Dem 2|1&4/B-C. (d) Dem 3|1&4/B-C. (e) Dem 1|2&3/B-C. (f) Dem 2|2&3/B-C. (g) Dem 3|2&3/B-C. (h) Dem 1|1&4/A-B. (i) Dem 2|1&4/A-B. (j) Dem 3|1&4/A-B. (k) Dem 1|2&3/A-B. (l) Dem 2|2&3/A-B.

using equations (2) and (3). Then, the importance coefficient of the wall is calculated according to formula (9), respectively, and the results calculated by different methods are compared. Finally, based on elastic-plastic strain energy, the effect of the seismic fortification intensity and the number of structural stories on the assessment of the wall is analyzed.

5.3.1. Importance Coefficient of the Wall. Figure 8 shows the transverse wall importance coefficient of the computation example. The calculation methods used for each wall from top to bottom include the elastic-plastic strain energy method (method one), the generalized elastic-plastic strain energy method (method two), the generalized stiffness method (method three), and the ultimate bearing capacity method (method four).

To understand the variation characteristic of the wall importance with plane position, by selecting the wall without openings between the B-axis and C-axis as an example, the analysis is as follows:

(1) Model MaS3-7 (0.1 g): the importance coefficient of the sidewalls obtained using the 4 methods is greater than that of the middle wall (1, 4 axis wall is the side wall and 2, 3 axis wall is the middle wall).

(2) Model MaS4-7 (0.1 g): the importance coefficient of the side wall of the bottom floor (1st, 2nd, and 3rd floors) obtained using method 1 is smaller than the middle wall, while the importance coefficient of the side wall of the upper floor (4th floor) is higher than the middle wall; the importance coefficient of the side wall of all floors obtained using method 2 is higher than that of the middle wall; the importance coefficient of the side wall of all floors obtained using method 3 is greater than that of the middle wall; the importance coefficient of the side wall of the bottom floor (the 1st and 2nd floors) obtained using method 4 is greater than that of the middle wall, while the importance coefficient of the side wall of the upper floor (3rd and 4th floor) is smaller than that of the middle wall.

(3) Model MaS3-8 (0.2 g): the importance coefficient of the side wall of the bottom floor (1st and 2nd floors) obtained using methods 1 and 2 is higher than that of the middle wall, while the importance coefficient of the side wall of the upper floor (3rd floor) is smaller than that of the middle wall; the importance coefficient of the side wall of all floors obtained using methods 3 and 4 is greater than the middle wall.

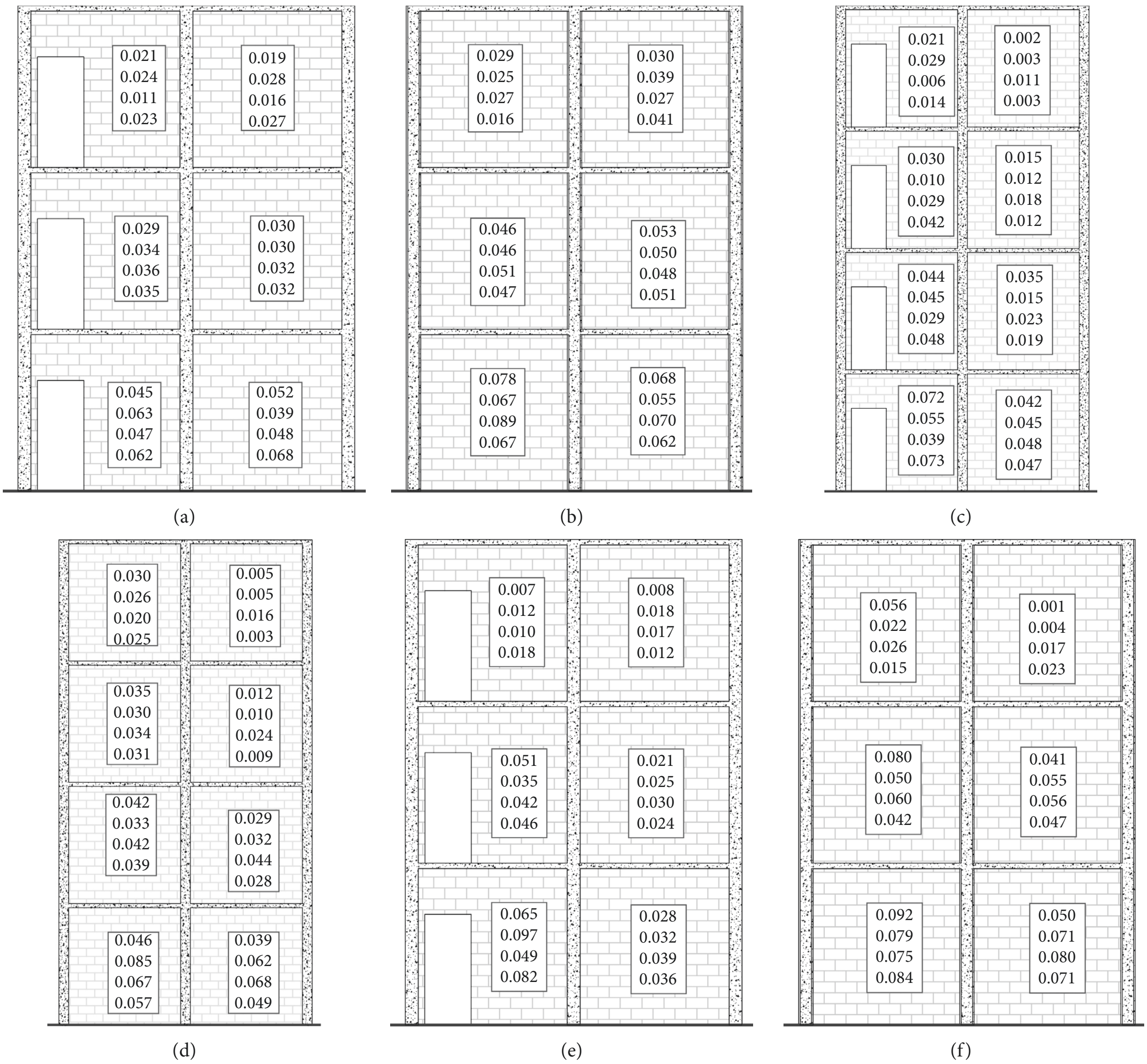

Figure 8: Calculation results of wall importance coefficient. (a) Axis 2&3 <MaS3-7 (0.1 g)>. (b) Axis 1&4 <MaS3-7 (0.1 g)>. (c) Axis 2&3 <MaS4-7 (0.1 g)>. (d) Axis 1&4 <MaS4-7 (0.1 g)>. (e) Axis 2&3 <MaS3-8 (0.2 g)>. (f) Axis 1&4 <MaS3-8 (0.2 g)>. *Note.* The importance coefficients of each wall in the figure are calculated using the elastic-plastic strain energy method, the generalized elastic-plastic strain energy method, the generalized stiffness method, and the ultimate bearing capacity method, respectively.

Since the elastic-plastic strain energy method and the generalized elastic-plastic strain energy method consider the stiffness degradation of the structure. Under severe earthquake, stiffness reduction of the side wall may be earlier than that of the middle wall, thereby making the side wall importance lower than that of the middle wall.

However, the stiffness degradation characteristics of the structure are not considered in the generalized stiffness method and the ultimate bearing capacity method. In the elastic stage, the side wall contributes more to the structural stiffness than the middle wall. Thus, when the generalized stiffness method or the ultimate bearing capacity method is employed, the side wall importance is higher than that of the middle wall.

As a result, the generalized stiffness method or the ultimate bearing capacity method is only suitable for the importance assessment of elastic structural members. In particular, when it is necessary to consider the plasticity performance of the structure under severe earthquake, it is more reasonable to employ the elastic-plastic strain energy method or the generalized elastic-plastic strain energy method.

Figure 9 shows the importance coefficient curve of the wall of example structure (MaS3-7 (0.1 g), MaS4-7 (0.1 g), and MaS3-8 (0.2 g)), which varies with the floor. This figure shows that whatever approach is used, the lower floor wall is more important than the upper floor wall. Besides, it is consistent with engineering experience.

5.3.2. Effect of the Seismic Fortification Intensity on the Importance of the Wall. To understand the effect of structural

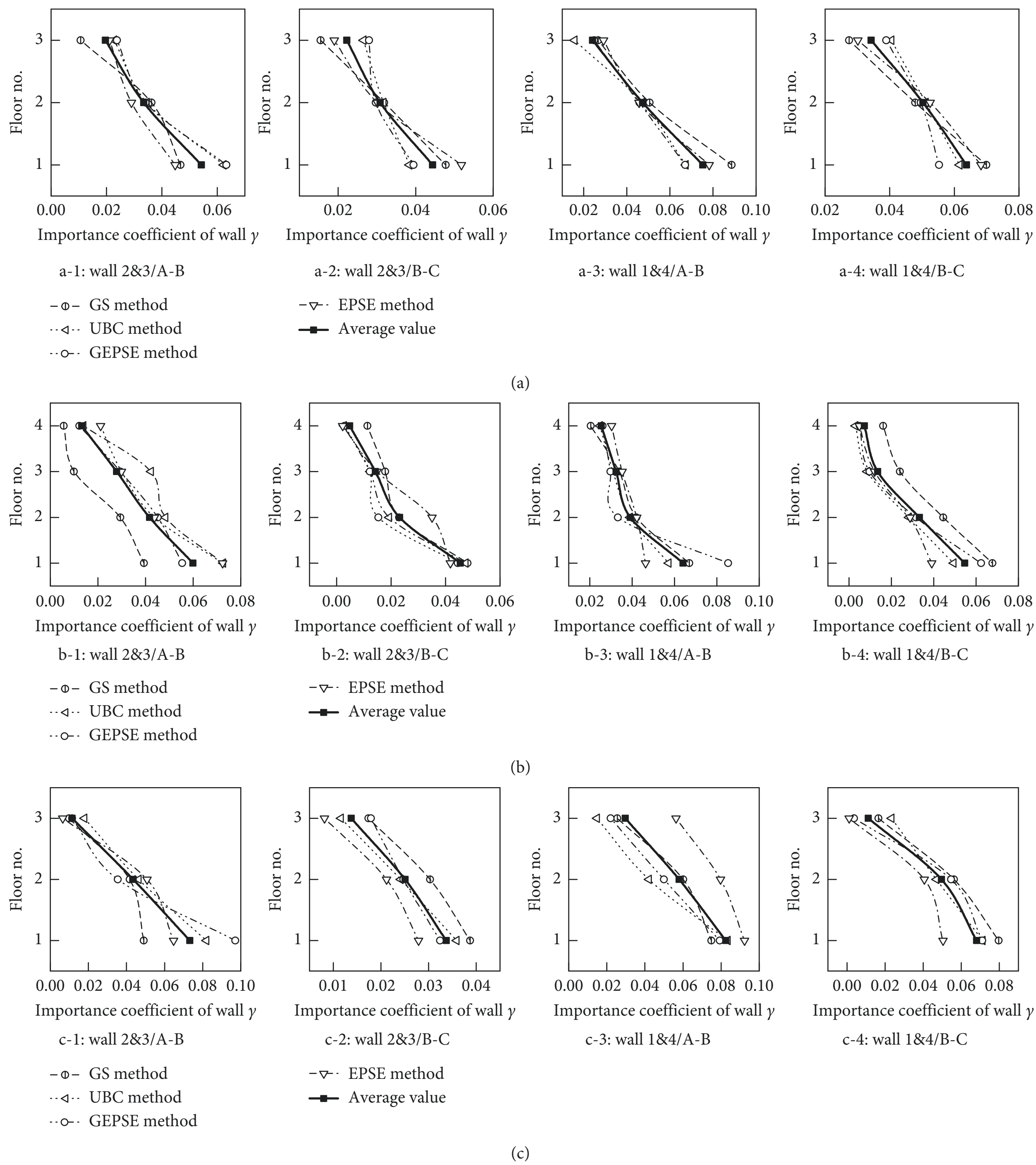

Figure 9: Variation curve of wall importance coefficient with floor. (a) Model MaS3-7 (0.1 g). (b) MaS4-7 (0.1 g). (c) MaS3-8 (0.2 g).

seismic fortification intensity on the importance assessment of the wall, example structures MaS3-7 (0.1 g) and MaS3-8 (0.2 g) are selected for comparison. The two models exhibit the same number of stories, and the seismic fortification intensity is 7 (0.1 g) and 8 (0.2 g), respectively. Figure 10 shows the comparison results of the importance coefficient of the wall with different seismic fortification intensities obtained using the elastic-plastic strain energy method. This figure shows that in the first and second stories of the structure, the greater the intensity of the seismic fortification intensity will be, the greater the importance coefficient of the wall between the A-axis and B-axis will be, and the smaller the importance coefficient of the wall between the B-axis and C-axis will be. In the third story of the structure, the importance coefficient of the wall decreases with the increase in seismic fortification intensity. Besides, the importance coefficient of the side wall between the A-axis and B-axis increases with the rise in fortification intensity.

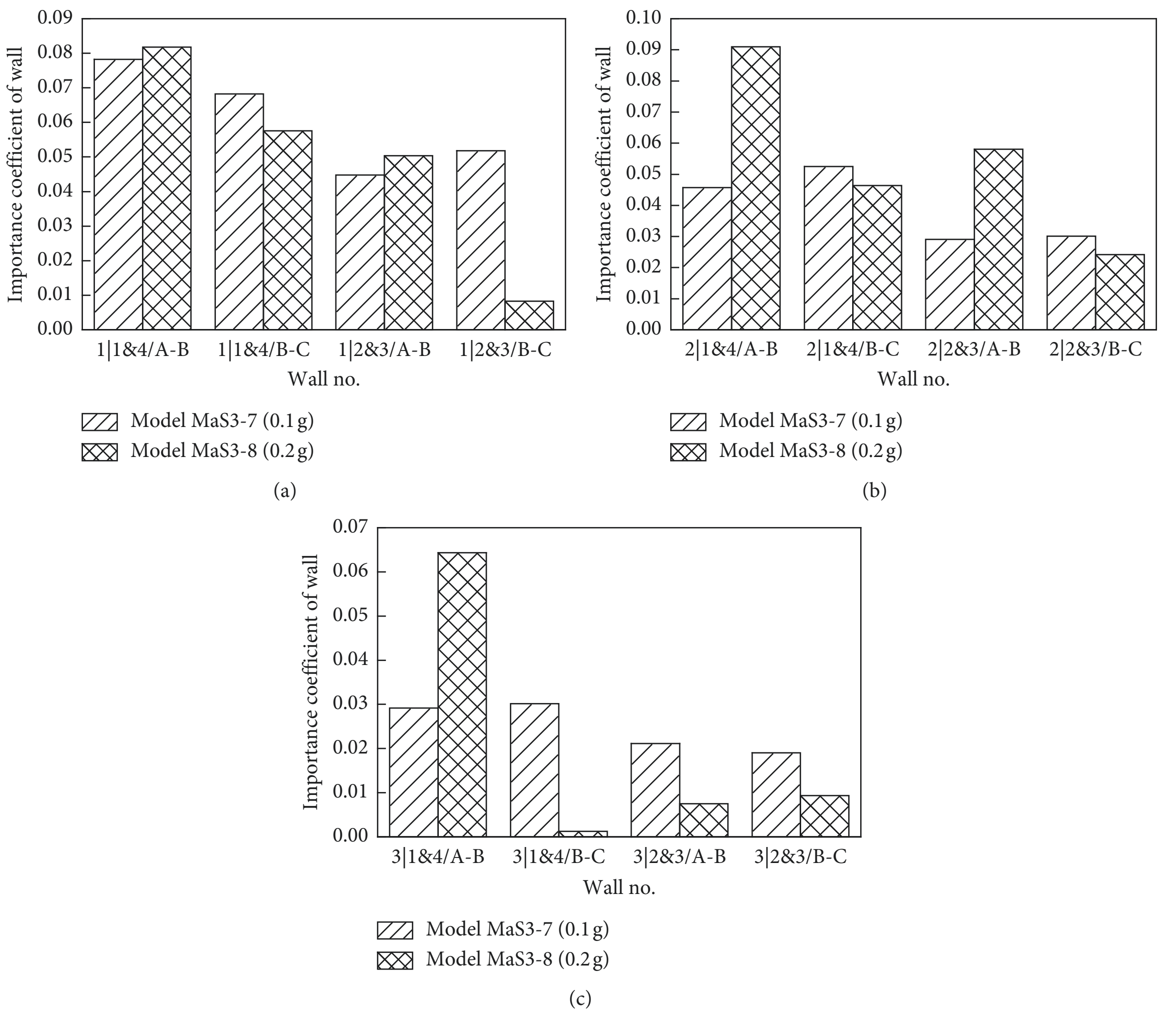

FIGURE 10: Importance coefficient of different fortification intensity structure wall. (a) 1st floor. (b) 2nd floor. (c) 3rd floor.

This reveals that the greater the seismic fortification intensity of the masonry structure is, the more important the wall of the bottom floor will be, and the less important the wall of the top floor will be.

5.3.3. Effect of the Number of Structural Stories on the Importance of the Wall. To understand the effect of the number of structural stories on the importance assessment of the wall, example structures MaS3-7 (0.1 g) and MaS4-7 (0.1 g) were selected for comparison. The two models have the same seismic fortification intensity, and the number of stories is three and four, respectively.

The importance of structural members is a relative conception. For instance, the magnitude of importance coefficient of a member is the same. If the number of a member in the structure is greater, the member will be more important. Accordingly, the magnitude of the member importance coefficient should be correlated with the number of members. Given the different number of model stories selected, the story member importance coefficient is defined as follows:

$$\eta_{i,j} = \frac{\gamma_{i,j}}{\sum_{j=1}^{m_i} \gamma_{i,j}}, \qquad (12)$$

where $\eta_{i,j}$ denotes the importance coefficient of the j-th member of the i-th story and m_i is the number of members of the i-th story.

Obviously, the story member importance coefficient only indicates the importance of the member in a certain floor. Figure 11 shows the comparison results of the story wall importance coefficient of structures which have different stories obtained using the elastic-plastic strain energy method. For the example structure 1&4/A-B (Figure 11(a): side wall and near-hole wall), on the bottom floor (1st and 2nd floors), there is a negative correlation between the total number of structural stories and the story member importance coefficient of the wall, while on the upper floor (3rd floor), the total number of structural stories is positively correlated with it. For the example structure 1&4/B-C (Figure 11(b): side wall and far-hole wall), the more the total number of structural stories, the smaller the story member importance coefficient of the wall. For the example structure 2&3/A-B (Figure 11(c): middle wall and opening wall), the more the total number of

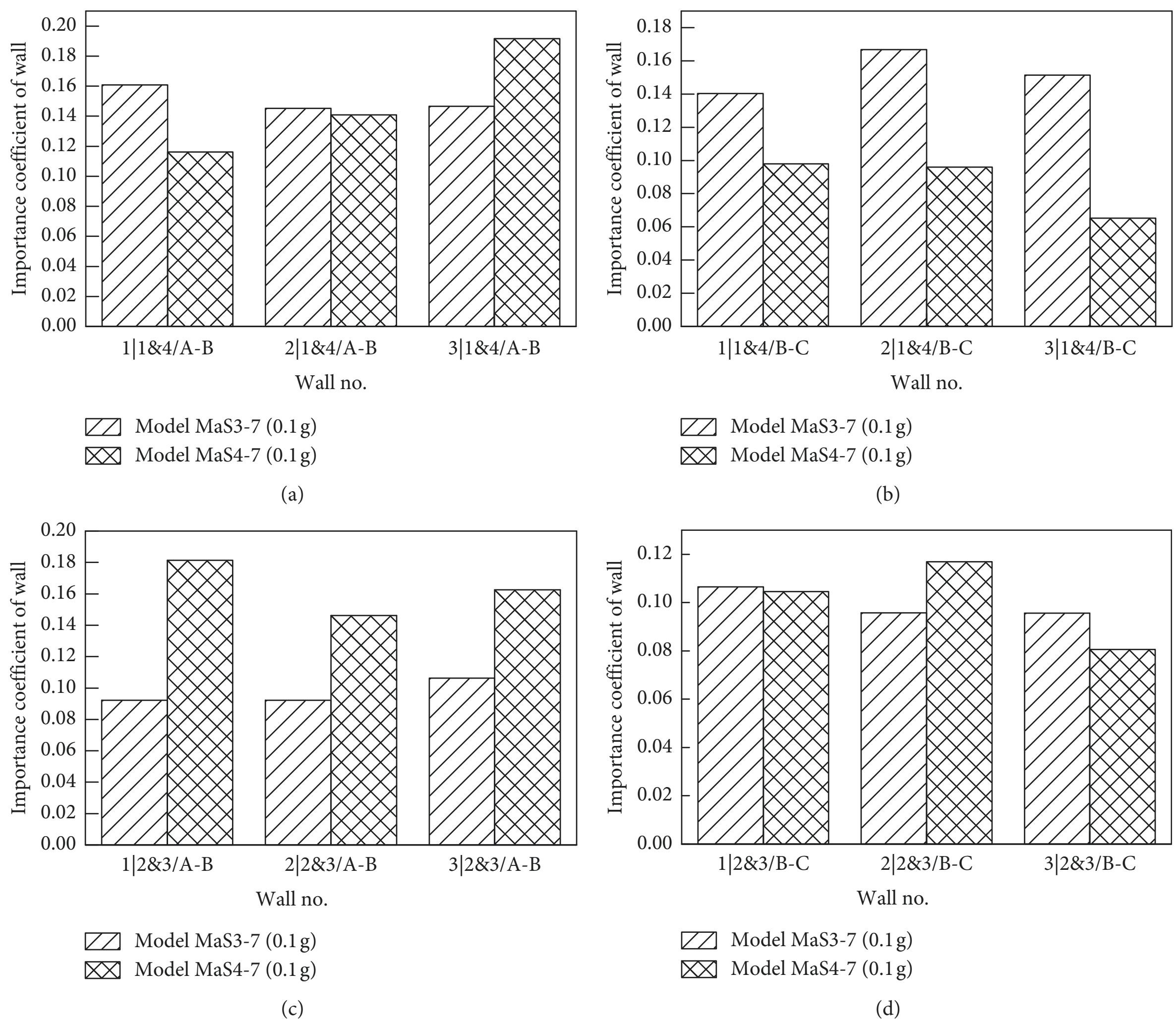

Figure 11: Floor wall importance coefficient of different layer structures. (a) Wall 1&4/A-B. (b) Wall 1&4/B-C. (c) Wall 2&3/A-B. (d) Wall 2&3/B-C.

structural stories, the greater the story member importance coefficient of the wall. For the example structure 2&3/B-C (Figure 11(d): middle wall and near-hole wall), on the bottom floor (1st and 2nd floors), there exists a positive correlation between the total number of structural stories and the story member importance coefficient of the wall, while on the upper floor (3rd floor), the total number of structural stories is negatively correlated with it.

In general, with the increase in the total number of structural stories, the story member importance coefficient of the opening wall and its adjacent wall increases. Comparatively, the wall without opening and the wall farther away from the opening wall have a smaller story member importance coefficient. This may be because opening holes in the bottom wall will impact the mechanical performance of the structure more significantly with the increase in the number of structural stories.

6. Conclusions

By pushover analysis of the structure, importance assessment of structural members based on elastic-plastic strain energy is a member importance assessment method in which the elastic-plastic strain energy serves as the structural performance parameter. This method has a clear physical meaning and can reflect the whole process mechanical characteristics when structure enters the elastic-plastic state under severe earthquake. The generalized elastic-plastic strain energy method is an approximate strain energy assessment method, and it is not suitable for the member importance assessment when the number of stories of the structure is relatively large.

The importance of the masonry structure wall is, respectively, assessed using the elastic-plastic strain energy method, the generalized elastic-plastic strain energy method, the generalized stiffness method, and the ultimate bearing capacity method. The results show the following:

(1) The generalized stiffness method and the ultimate bearing capacity method do not consider the stiffness degradation characteristics of the structure. It is only suitable for the structural analysis at the elastic stage. At the same time, the elastic-plastic strain energy method and the generalized elastic-plastic strain

energy method can reflect the stiffness degradation characteristics of the structure.

(2) The wall of the bottom floor is more important than that of the upper floor. Moreover, the higher the seismic fortification intensity is, the more important the wall of the bottom floor will be, and the less important the wall of the upper floor will be. Furthermore, the more the total number of structural stories is, the more important the opening wall and its adjacent wall will be, and the less important the wall without opening and the wall farther away from the opening wall will be.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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