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EARTHQUAKE RESPONSE PREDICATION AND RETROFITTING TECHNIQUES OF ADOBE STRUCTURES

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SUMMARY

Collapses of adobe structures due to earthquakes have resulted in tremendous losses of human life and property. How to improve the earthquake resistibility of adobe structures is a severe technical problem for our earthquake engineers. In this study, first a methodology for the earthquake response analysis of adobes has been proposed. Anisotropic hyperbolic equation is utilized for expressing the material properties of adobe bricks. A kind of viscoelastic joint element is proposed for modeling the opening and closing behaviors of the interfaces between the bricks. Then, as an application, an unreinforced adobe house is analyzed with the proposed method, and several failure modes are classified based on the analytic results. Finally, a proposal of retrofitting measures with wooden frames is given, and its efficiency is verified.

INTRODUCTION

Adobe house is a traditional living structure in majority of developing countries for its material availability and living amenity, etc. However, poor earthquake resistibility is its fatal fault, which makes this kind of buildings to be evaluated as highest risk in the world. The research on adobe structures started from the early 1930's, and recent years it becomes relatively active. Many damage surveys were performed [1][2] and some methodologies for the seismic capacity evaluation are proposed [3]. These studies provide us with valuable information on the earthquake resistibility assessment of this kind structure. But the progress for improving the seismic resistibility is not as big as it should be. The research on this problem is preliminary compared with those of other kind structures. It is pointed out by Kuroiwa [4] that no effective progress has been made in reducing the seismic risk of those people living in adobe houses. The earthquake occurred on Dec.26, 2003 in Iran killed about 50 thousand people reminds us again that our earthquake engineers should pay more attention to the developing countries where much more technical problems need our efforts.

From historical earthquake events it is estimated that the collapses of the adobe structures are mainly due to the following three reasons, among others: 1). Adobe is a kind of brittle material. Its tensile strength and ductility are very low even thought a relatively high compressive strength can be expected. 2). The

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connection between the bricks is extremely weak, which result in a partially or totally disintegration under a few cycles of shaking of a moderate earthquake. 3). Heavy mass inducing great inertial force and configuration of the walls derives an unstable structure. However, there have been no comprehensive interpretations on the failure mechanisms. One of the most possible reasons is lack of a suitable methodology for simulating the dynamic behaviors of adobe structures during earthquakes.

In this study, for predicating the earthquake responses of adobe structures, a numerical method has been developed, where nonlinear finite element method is utilized and the discontinuity of the interfaces between adobe bricks is considered. Then, the methodology is applied to estimate the earthquake responses of an adobe house. Finally, a retrofitting technique with wooden frame is proposed and its efficiency is verified.

METHODOLOGY FOR EARTHQUAKE RESPONSE ANALYSIS

Based on the theory of finite element method and the principle of discontinuities, a 3-D nonlinear analytic method is developed for analyzing the earthquake responses of adobe structures. In the method, the adobe brick is modelled with finite elements, and the interface between the bricks is modelled with a kind of viscoelastic joint element proposed in the study, which can simulate the opening and sliding behaviors of the interfaces. Since the roof of ordinary house is usually light and there is nearly no restricting connection between the roof and walls, roof is not modeled in the numerical model. But openings such as doors and windows are considered. Fig.1 shows the configuration of the analytic model. The essential points of the method are mentioned briefly herein.

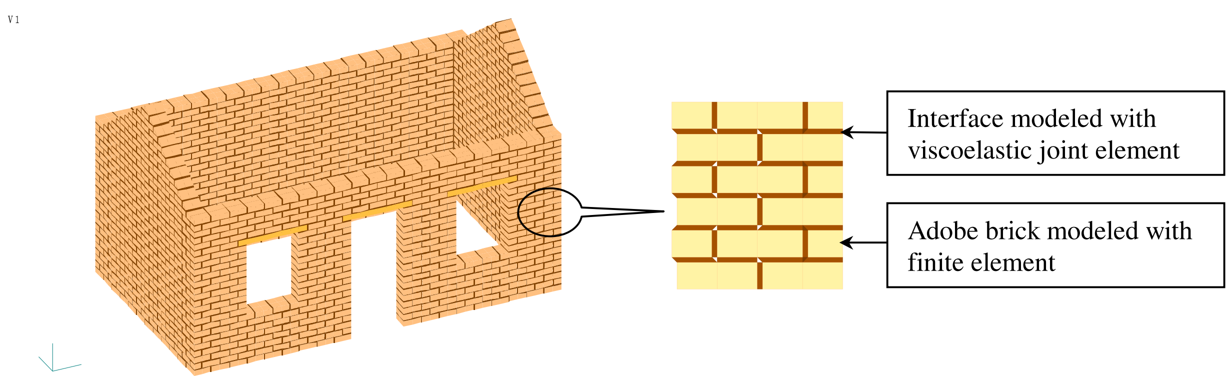


Fig.1 Analytic Model

Modelling of interfaces

For modelling the interfaces between the bricks, a viscoelastic joint element is proposed in the study with reference to the joint theory presented by Zienkiewicz et al [5]. It is treated essentially like a solid element, but its thickness can be set at a very small value or zero, and the constitutive matrix is determined in a different way from that of solid element. The most characteristic point is that the attenuation of vibrating energy is considered in the element. The schematic diagram of the element is shown in Fig.2, and its dynamic properties in the normal direction and shear direction are shown in Fig.3.

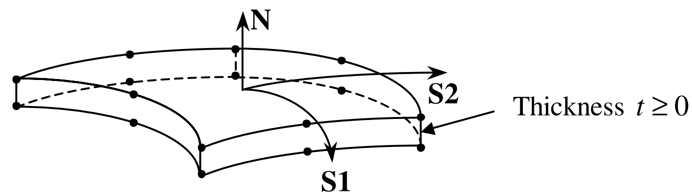
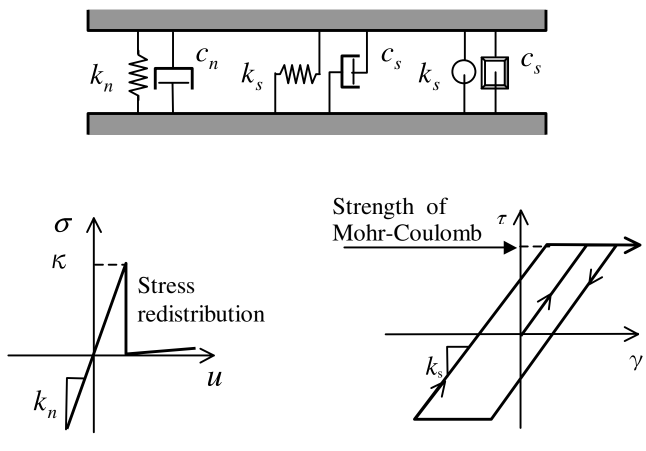


Fig.2 Viscoelastic joint element



(b) property in normal direction

(c) property in shear direction

Fig.3 Dynamic Properties

As shown in Fig.3, the 3-D viscoelastic joint element is expressed mechanically with 3 springs and 3 dampers. k_n and k_s denote the normal direction stiffness and shear direction stiffness respectively. Factor c_n and c_s are damping coefficients. Therefore, the constitutive equation is expressed in an increment form as

$$\{\Delta\sigma_j\} = [K_j]\{\Delta u_j\} \tag{1}$$

where, $\{\Delta\sigma_j\}$ and $\{\Delta u_j\}$ are the vectors of increments of stresses and strains, and $[K_j]$ is the constitutive matrix, which can be expressed with the normal and shear stiffness components

$$[K_j] = \begin{bmatrix} k_s & 0 & 0 \\ 0 & k_s & 0 \\ 0 & 0 & k_n \end{bmatrix} \tag{2}$$

In the normal direction of an element, it shows an elastic-plastic property. When the normal stress is negative, i.e. in compressive state, for preventing the geological media from overlapping, a high value of the normal stiffness k_n is assumed. Oppositely, when tensile stress excesses the initial tensile strength supposed for media in the interfaces, opening of the joint element will occur, and the normal stiffness will reduce to zero (in calculation, a small value of the order 10^{-3} is used). Once the element opened, the initial tensile strength of the interface losses, consequently the joint element will open again whenever tensile stress occurs. About the sliding behavior, whether it slides or not depends on the ratio between the shear stress and the shear strength defined by Mohr-Coulomb criteria. Whenever the joint opened or slid, stress redistribution will be performed for keeping the balance of inertial forces.

Simultaneously, it is also assumed that the interface between adobe bricks has a vibrating energy attenuation feature. Some loss will occur when vibrating wave propagates through the interface. Such damping is defined as stiffness proportional with the following form

$$c_n = \frac{2h_j}{\omega_1} k_n \qquad c_s = \frac{2h_j}{\omega_1} k_s \tag{3}$$

where, ω_1 denotes the first natural circular frequency of a adobe structure. h_j indicates the damping coefficient depending on the normal stress of the interface, and which is defined by

$$h_j = \left(2 - \frac{\sigma_n}{2\sigma_{0m}} \right) h_0 \qquad h_j \geq h_0 \tag{4}$$

where, σ_{0m} indicates the mean value of the initial normal stresses of all of the interfaces, and h_0 is the mean initial damping coefficient of adobe material. It is clear that the damping coefficient of interface will vary from h_0 when the normal stress equals to or exceeds the value of 2 times of the mean initial normal stress, to $2h_0$ when the interface is in the status just before opening.

Constitutive equation of adobe bricks

Based on the laboratory tests, Islam and Watanabe [6] have given the dependencies of shear modulus and damping coefficient on the shear strain and confining stress (Fig.4). Such relationships have been expressed with hyperbolic functions. It was also pointed out that equivalent linearization method generally gives a satisfied simulation on the laboratory tests.

However, as well known, equivalent linearization method is usually used in the analyses of massive structures such as rock-fill dam, soil foundation, etc. For adobe structures, since the walls are usually very thin, and adobe bricks are generally in a status of plane stress, naturally anisotropy exists. Therefore, in the following numerical analyses, anisotropy of the material properties is considered. The dependencies of shear modulus and damping coefficient are given by

$$G_i = G_{i0} \frac{1}{1 + \gamma_{ie} / \gamma_{ir}} \qquad (i = x-y \quad plane, \quad y-z \quad plane, \quad z-x \quad plane) \tag{5}$$

$$h_i = h_{i\max} \frac{\gamma_{ie} / \gamma_{ir}}{1 + \gamma_{ie} / \gamma_{ir}} \qquad (i = x-y \quad plane, \quad y-z \quad plane, \quad z-x \quad plane) \tag{6}$$

where, G and G_0 are current shear modulus and initial shear modulus in each plane. γ_e and γ_r are equivalent shear strain ($\gamma_e = 0.67\gamma_{\max}$) and reference shear strain respectively. h and $h_{\max}$ denote the current damping coefficient and the maximum damping coefficient respectively.

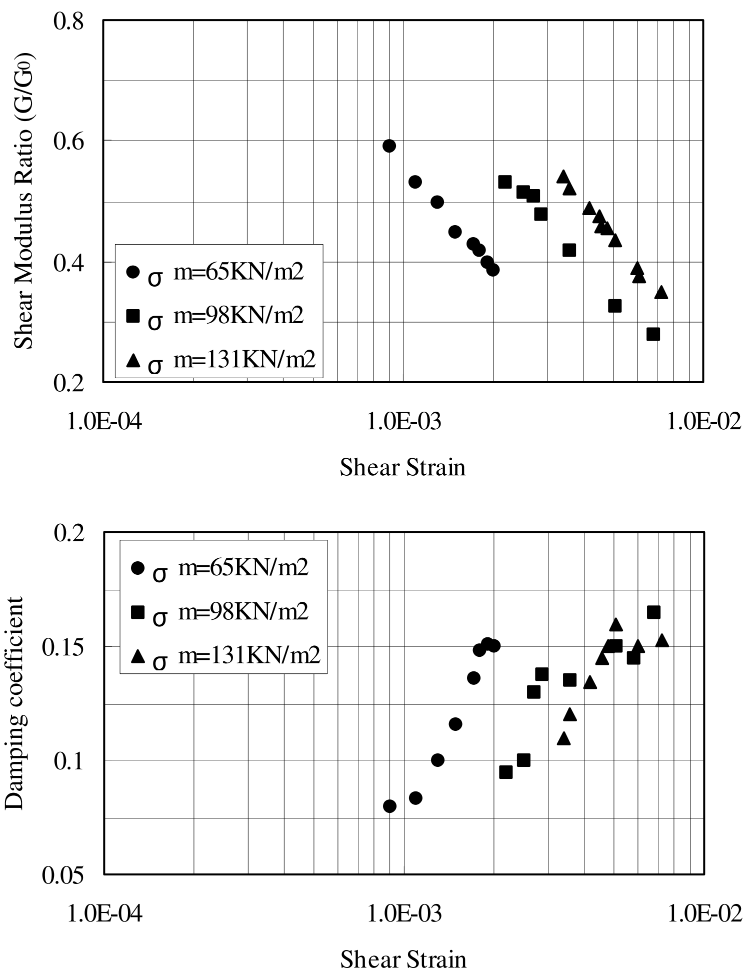


Fig.4 Dependency of shear modulus and damping coefficient on shear strain (Islam and Watanabe [7])

About the initial shear modulus, it is supposed to be depending on the mean effective stress in the form

$$G_{i0} = 470\frac{(2.17-e)^2}{1+e}(\sigma_{im})^{0.68} \qquad (i = x-y \quad plane, \quad y-z \quad plane, \quad z-x \quad plane) \tag{7}$$

where, σ_{im} is the mean effective confining stress in each plane, and e indicates the void ratio of adobes.

Solving of motion equation

From the above discussions, it is obvious that an adobe structure consists of nonlinear adobe bricks and nonlinear interfaces. In numerical analysis, it will take long calculating time to get a converged solution for such complicated system. Herein, for increasing the calculating speed, the convergence processes for adobe bricks and interfaces are separated. First, the interface is treated as linear one until the material properties of adobe bricks converged. Then, the nonlinear calculation concerning the interfaces is processed with the converged adobe material properties.

FAILURE MODE ANALYSIS OF A UNREINFORCED ADOBE HOUSE

Analytic conditions

Model

With the proposed methodology, the earthquake response of a typical adobe house shown in Fig.5 is analyzed. The house is modeled with 6148 solid elements and 8984 joint elements.

First, a static analysis is carried out, from which the mean effective confining stress of every solid element is got. As an example, Fig.6 gives the confining stress distribution in the z-x plane. The initial shear modulus of adobe bricks is determined according to equation (7). Table 1 shows the dynamic properties of adobe bricks, and Table 2 shows those of interfaces (joint elements). The house is fixed on ground surface, and the ground earthquake motion is input here.

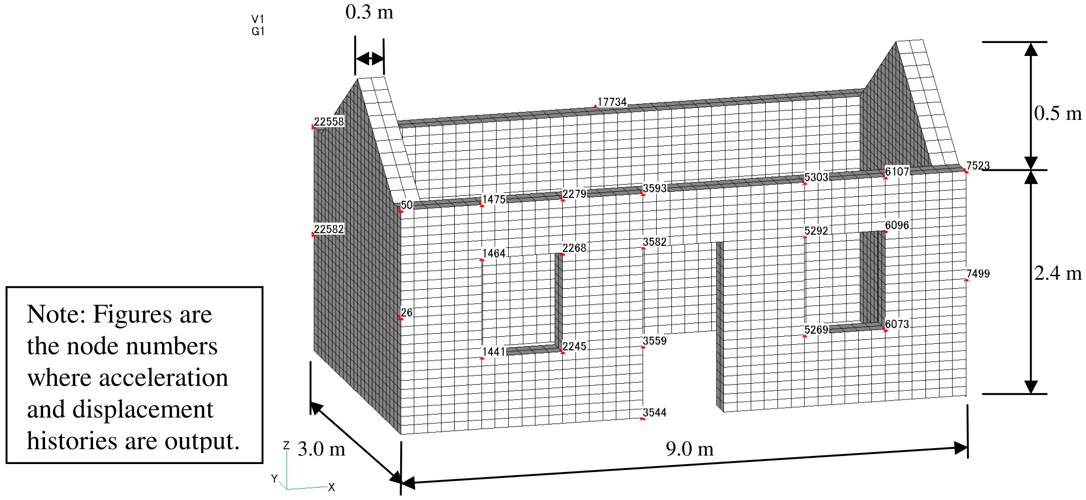


Fig.5 Model used in the analysis

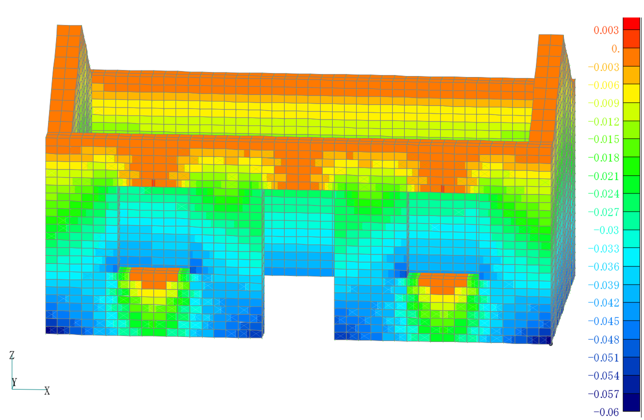


Fig.6 Distribution of the confining stress in the z-x plane (MPa)

Table 1 Dynamic properties of adobe bricks

Density (g/cm^3)	Poisson's ratio	Maximum damping coefficient	Reference shear strain
2.0	0.35	18%	0.0003

Table 2 Dynamic properties of joints

<table>
<tr><th rowspan="2">Normal stiffness (N/mm^3)</th><th rowspan="2">Shear dir. stiffness (N/mm^3)</th><th rowspan="2">Cohesive force c (MPa)</th><th rowspan="2">Angle of internal friction</th><th colspan="2">Residual strength parameter</th><th rowspan="2">Initial tensile strength (MPa)</th></tr>
<tr><th>cohesive force c'</th><th>Angle of internal friction</th></tr>
<tr><td>10^8</td><td>$5*10^7$</td><td>0.1</td><td>30.0</td><td>0.0</td><td>30.0</td><td>0.05</td></tr>
</table>

Earthquake wave

The earthquake wave of EL-Centro NS 1954 is used. The maximum acceleration amplitude is adjusted at 2 levels, i.e., 150 $cm/\sec^2$ and 300 $cm/\sec^2$. The length of wave used in the analysis is 10.24 sec., and the time interval is 1/100 sec. The earthquake is input in the right-left direction and back-forth direction respectively.

Failure modes

Fig.7 shows the tensile stress distribution of the front wall when the earthquake of the maximum acceleration 150 $cm/\sec^2$ struck the house in the right-left direction. It can be found that tensile stresses concentrated in the areas around the corners of the door and windows. But the earthquake of this level (150 $cm/\sec^2$) did not initiate the collapse of the house, though the opening and closing behavior of the joints was found in the corner areas during the earthquake.

However, despite of the shaking direction, the house collapsed when it was struck by the earthquake of the maximum acceleration of 300 $cm/\sec^2$. Fig.8 shows the deformation just before the collapse of the house when the earthquake shaken in the right–left direction. Fig.9 shows that when the earthquake struck the house in the back-forth direction.

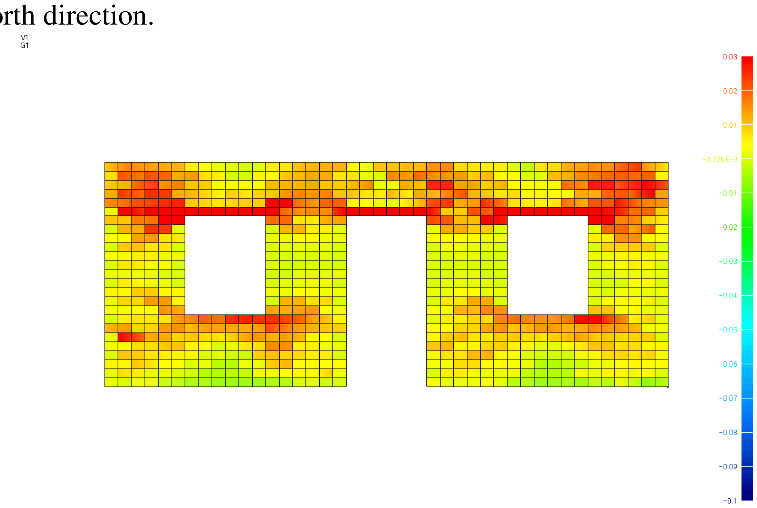


Fig.7 maximum tensile stress distribution (MPa)

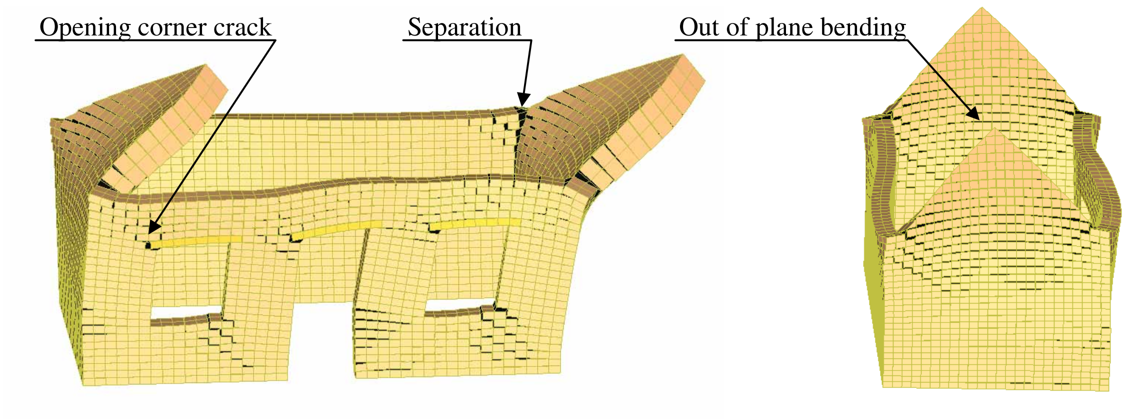


Fig.8 Deformation just before the collapse of the house when earthquake of the maximum acceleration 300 $cm/\sec^2$ shakes in the right-left direction

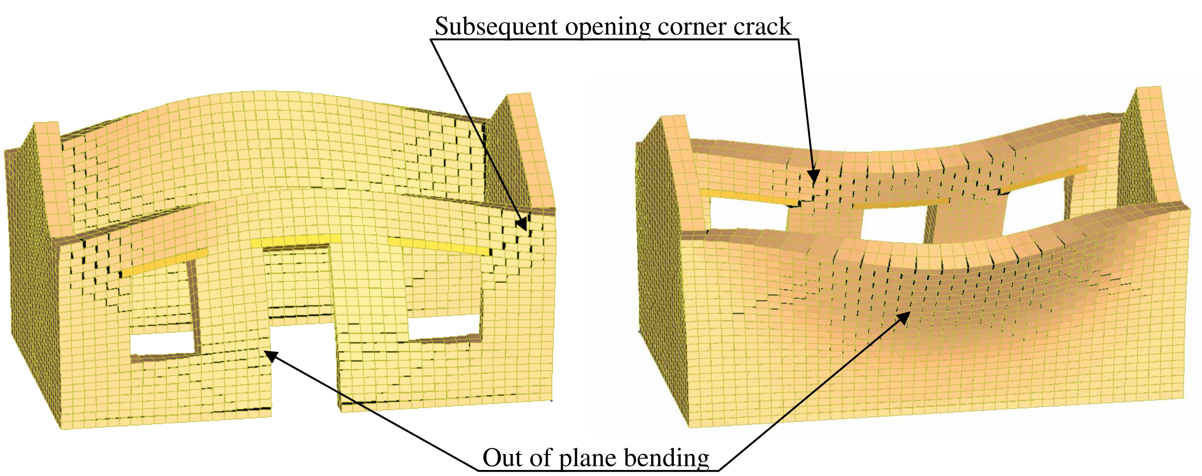


Fig.9 Deformation just before the collapse of the house when earthquake of the maximum acceleration 300 $cm/\sec^2$ shakes in the back-forth direction

From Fig.8 and Fig.9, it was found that before the breakage of adobe bricks, the interfaces between adobe bricks opened. Interfaces presented much weak responses than the adobe brick themselves. Interface opening emerged in the every one of the following failure modes.

Separation of walls

When earthquake shaken in the right-left direction, the separation at the junctures of the longitudinal walls and the gable walls occurred. Separation started from the tops of the junctures. With the extension of the shaking time and the increment of shaking intensity the separation extended vertically downward until the collapse of the house. Although the physical connection at the junctures of the walls is considered in the model, this type of failure is still dominant.

Out of plane bending

Despite of the shaking direction, out of plane bending failure mode was found. When earthquake shaken in the right-left direction, the right and left gable walls rotated, which induced horizontal cracks in the upper half of the walls. With the increment of the ground motion intensity, the top triangular parts of the gable walls bent. Whereas, out of plane bending failure occurred in the longitudinal walls when earthquakes shaken in the back-forth direction. Front wall bent at the height of windowsill and the rear wall bent at the middle height of the wall. But no serious damage was found in the gable walls when the earthquake shaken in the back-forth direction.

Opening corner crack
Serious opening corner cracks occurred independently on the shaking direction. But with the variation of shaking direction, the mechanism of such failure changed. When the house shaken along the longitudinal direction, opening corner cracks occurred due to shear stress concentration in the area. Oppositely, when earthquake shaken in the direction perpendicular to the longitudinal walls, such cracks occurred due to the tensile stress concentrated. This kind of tensile crack is inferred to be a subsequent result of the failure mode "out of plane bending".

PROPOSAL OF RETROFITTING TECHNIQUES

Retrofitting measures

Based on the above analyses, several retrofitting measures are under study in JPBS (JP Business Service Corporation Ltd.) and Saitama University. For improving the dynamic material properties of adobes, some reinforcement materials such as gypsum and straw, etc. are used. And for improving the structural stability, some measures such as concrete and wooden frames, columns, etc. are being considered. It is thought that a retrofitting technique should raise the earthquake resistibility effectively with least cost increment. The technique should use the material available in the developing countries, especially in rural areas, and it should be easy for the owners of no specialized knowledge to master it. Herein, the retrofitting technique with wooden frame is proposed.

Fig.10 shows the wooden frame. Its main function is supposed to increase the integration of bricks and that of walls. However, what position it should be set for exerting most effectively? Two ways are tried, and the retrofitting effects are examined and compared here. One (called "Method 1" later in the paper) is that setting it at the top of openings, since opening corner crack is a very common failure mode. And the other (called "Method 2" later) is setting it at the top of the wall, since separation of the walls begins from the top of the junctures. As the prerequisites, the junction between the frame and adobe bricks should be so good that no slippage and no separation is allowed.

As for the material properties of the frame, they are supposed to be linear, and the values are shown in Table 3.

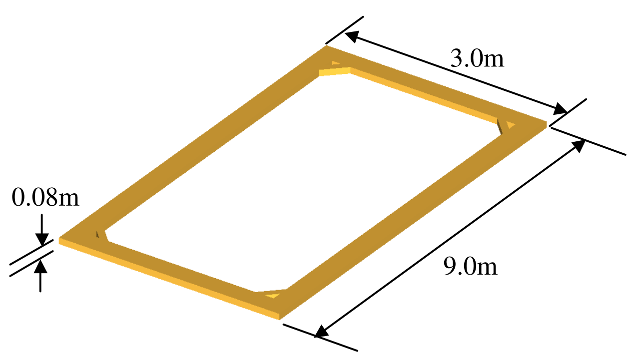


Fig.10 Wooden frame used for retrofitting

Table 3 Material properties of wooden frame

Shear modulus (MPa)	Density (g/cm^3)	Poisson ratio	Damping coefficient (%)
3700.0	0.85	0.25	5.0

Retrofitting effects

By inputting the same earthquake motions as used before (EL-Centro NS wave of the maximum acceleration 150 $cm/\sec^2$, 300 $cm/\sec^2$), the responses of the retrofitted adobe house are analyzed. It was found that no collapse occurred in all of the cases when the maximum acceleration of the earthquake was 150 $cm/\sec^2$. Comparison of the two retrofitting measures shows that the maximum relative displacements of the top of the gable walls are 6.61 cm and 2.93 cm respectively when the earthquake shaken in the right-left direction. Although the interfaces of the bricks in the corner areas of door and windows opened, they closed after the earthquake.

The retrofitted house collapsed only in the case of "Method 1" and struck by the earthquake of the maximum acceleration 300 $cm/\sec^2$ in the right-left direction, where the top of the gable walls fallen down. Table 4 shows the analytic results.

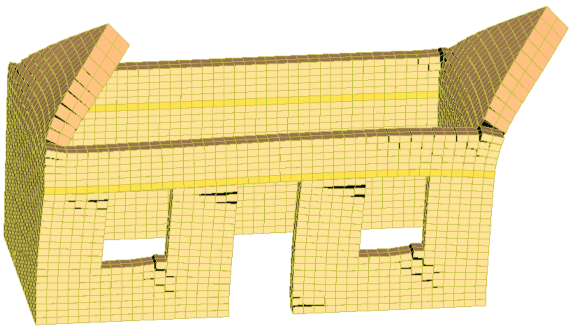
Table 4 Analytic results when the maximum earthquake acceleration was 300 $cm/\sec^2$

Retrofitting measure	Shaking direction	
	Right-left	Back-forth
Method 1	The top of the gable walls fallen down	Concentrated shear damage at the bottom of the walls occurred, but no collapse
Method 2	Crack in the opening corner area occurred, but no collapse	Horizontal cracks occurred in the upper part of the longitudinal walls, but no collapse

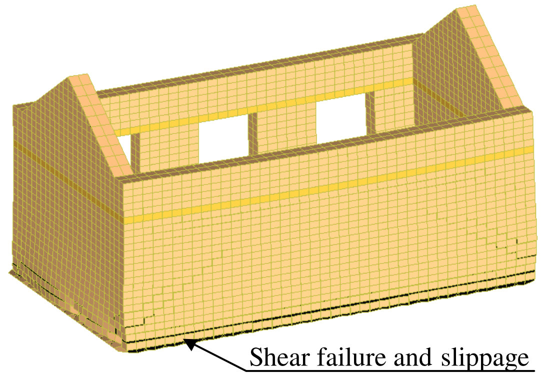
For the case of retrofitting with "Method 1", Fig.11(a) shows the deformation just before the falling down of the top of the gable walls when the earthquake shaken in the right-left direction, and Fig.11(b) shows the maximum deformation of the retrofitted house when the earthquake shaken in the back-forth direction. Fig.12(a) and (b) shows the maximum deformations of the house retrofitted with "Method 2" when earthquake shaken in the right-left direction and back-forth direction respectively.

It was found that with "Method 1", i.e., setting the frame at the top of the openings, the bricks in the opening corner area are confined, and the separations of the walls are restricted in some sort. Although the top of the gable walls fallen down when earthquake of the amplitude of 300 $cm/\sec^2$ shaken in the right-left direction, the damage was much reduced in the area above the frame in the longitudinal walls. On the contrary, when the earthquake shaken in the back-forth direction, shear failure of adobe bricks and slippage were found at the bottom 2 layers, while no any obvious damage was found at the upper part of the house. From the comparison of Fig.9 and Fig.11(b), it is inferred that the frame increased the flexural stiffness of the longitudinal walls, consequently the failure mode "out of plane bending" did not appear. Generally say, this retrofitting method has integrating function to the walls, and can increase the flexural stiffness of the upper parts of the house significantly.

By comparing Fig.12 to Fig.8 and Fig.9, it can be found that setting the frame at the top of the wall also given a satisfied performance. Particularly, the separation between the gable walls and longitudinal walls did not appear at all. And the deformation of the walls reduced remarkably. When earthquake shaken in the right-left direction, the separation behaviors of the interfaces around the top corners of the door and windows were much tempered, although no obvious relaxation was viewable at the lower corners of the openings. On the other hand, when the earthquake shaken in the back-forth direction, the house performed stably as a whole. However, from Fig.12(b) it can be found that horizontal cracks in the zone over the middle height of the longitudinal walls occurred.

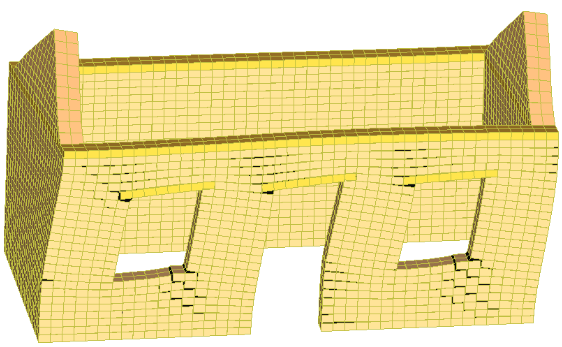


(a) Shaken in right-left direction

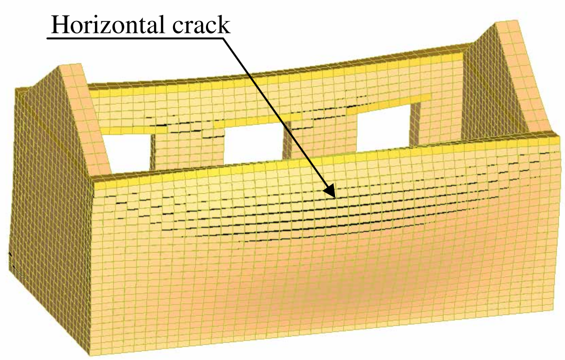


(b) Shaken in back-forth direction

Fig.11 Deformation of the house retrofitted with "Method 1"



(a) Shaken in right-left direction



(b) Shaken in back-forth direction

Fig.12 Deformation of the house retrofitted with "Method 2"

It is difficult to judge which of the two methods is better simply. It is conjectured that for a high house the "Method 2" may be better, and vice versa. Anyway, a strong adobe house should be built in a reasonable configuration and with earthquake retrofitting measures.

It is clear that the retrofitting techniques proposed in the study can improve the earthquake resistance of adobe houses remarkably. Other additional measures such as adding corner wooden columns, etc., may strengthen the adobe house, and their effects are under investigation at present. But taking account of the balance of effectiveness and its cost and applicability, the measures proposed in the paper are considered to be reasonable.

Meanwhile, if concrete frame is available or corner column can be adopted, the earthquake resistibility of an adobe house may be improved much more. The reports of such investigations are expected in the future.

CONCLUSIONS

The methodology proposed in the study is a useful way to predicate the earthquake responses of adobe structures, or to verify the effects of retrofitting measures.

The retrofitting measures proposed in the study are applicable and effective for improving the earthquake resistibility of adobe structures. Earthquake disaster reduction can be expected with the measures.

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