EARTHQUAKE RESPONSE PREDICATION AND RETROFITTING TECHNIQUES OF ADOBE STRUCTURES

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SUMMARY

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.

ANALYTIC METHOD

For modelling the interfaces between the bricks, a viscoelastic joint element is proposed in the study. It is treated essentially like a solid element, but the constitutive matrix is determined in a different way. The schematic diagram of the element and its dynamic properties in the normal and shear directions are shown in Fig.1.

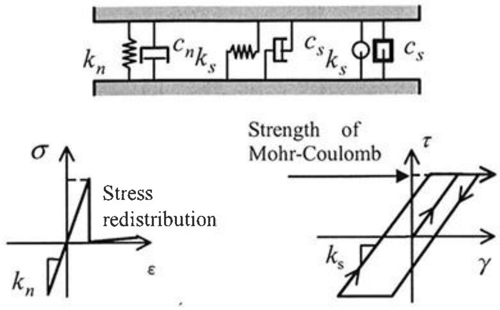
As shown in Fig.1, the 3-D viscoelastic joint element is expressed mechanically with 3 springs and 3 dampers. k_n and k_s denote the normal direction stiffness and shear direction stiffness respectively. Factor c_n and c_s are damping coefficients. Therefore, the constitutive equation is expressed in an increment form as

$$\{\Delta\sigma_j\} = \lfloor K_j \rfloor \{\Delta u_j\} \tag{1}$$

where, $\{\Delta\sigma_j\}$ and $\{\Delta u_j\}$ are the stress and strain increment vectors, and $\lfloor K_j \rfloor$ is the constitutive matrix, which can be expressed with the normal and shear stiffness components

$$\lfloor K_j \rfloor = \begin{bmatrix} k_s & 0 & 0 \\ 0 & k_s & 0 \\ 0 & 0 & k_n \end{bmatrix} \tag{2}$$

When the normal stress is in compressive state, 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). 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.



(a) in normal direction (b) in shear direction

Fig.1 Dynamic properties of viscoelastic joint element

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 an adobe structure. h_j indicates the damping coefficient depending on the normal stress of the interface.

FAILURE MODES OF AN ADOBE HOUSE

An adobe house, of 9 meters in length, 3 meters in breadth, 2.4 meters in height and 0.3 meters in wall thickness, was analyzed. The earthquake wave of EL-Centro NS 1954 is used, and the maximum acceleration is adjusted at 300 $cm/\sec^2$. The earthquake is input in the right-left direction and back-forth direction respectively.

Despite of the shaking direction, the house collapsed. Fig.2 shows the deformation just before the collapse of the house.

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 and 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, and finally, the top triangular parts of the gable walls bent. On the other hand, 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

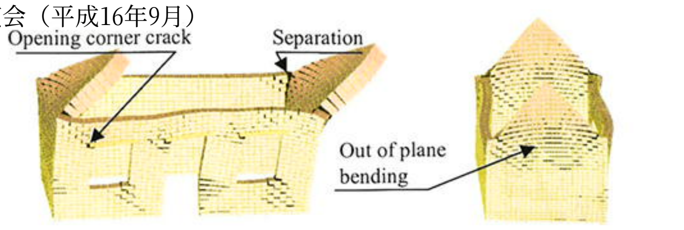
Serious opening corner cracks. When the house shaken along the longitudinal direction, opening corner cracks occurred due to shear stress concentration in the area. Oppositely, when earthquake shaken in the direction perpendicular to the longitudinal walls, such cracks occurred due to the tensile stress concentrated. This kind of tensile crack is inferred to be a subsequent result of the failure mode “out of plane bending”.

RETROFITTING TECHNIQUES

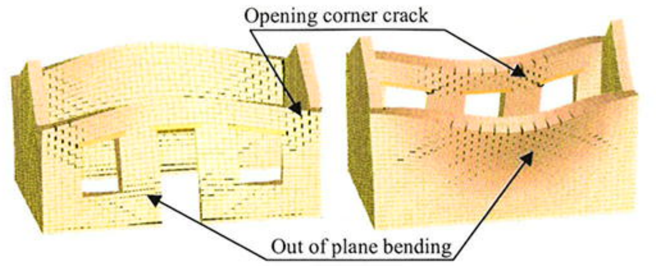
For improving the earthquake resistibility of adobe houses, two retrofitting methods with wooden frame are proposed in the study. One (called “Method 1” later) is setting a wooden frame at the top position of the door and windows, and the other (called “Method 2” later) is setting the frame at the top of the longitudinal walls.

The retrofitted house collapsed only in the case of “Method 1” when struck by the earthquake in the right-left direction, where the top of the gable walls fallen down. Fig.3(a) shows the deformation just before the collapse, and Fig.3(b) shows the maximum deformation of the retrofitted house when the earthquake shaken in the back-forth direction. Fig.4(a) and (b) shows the maximum deformations of the house retrofitted with “Method 2”.

It was found that with “Method 1”, 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 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 of interfaces were found at the bottom 2 layers. 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.

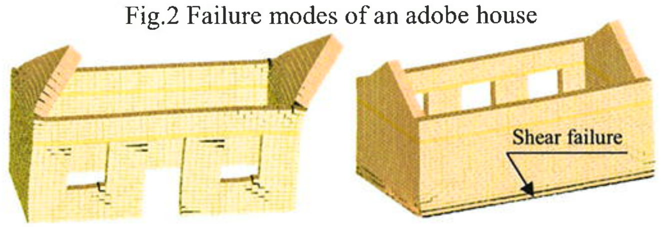


(a) When shaken in right-left direction



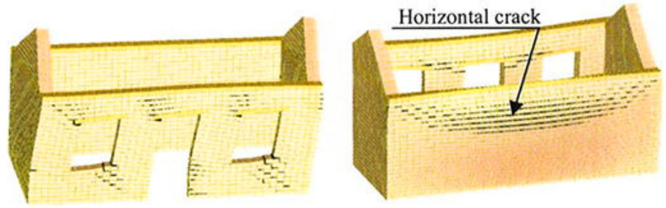
(b) When shaken in back-forth direction

Fig.2 Failure modes of an adobe house



(a) in right-left direction (b) in back-forth direction

Fig.3 Deformation of the house retrofitted with method 1



(a) right-left direction (b) in back-forth direction

Fig.4 Deformation of the house retrofitted with method 2

It can be found that setting the frame at the top of the longitudinal walls 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. On the other hand, when the earthquake shaken in the back-forth direction, the house performed stably as a whole. Only some horizontal cracks in the upper parts of the longitudinal walls occurred.

CONCLUSIONS

The methodology proposed in the study is a useful way to predicate the earthquake responses of adobe structures. The retrofitting measures proposed in the study are applicable and effective for improving the earthquake resistibility of adobe structures.