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FEM SIMULATION OF SEISMIC BEHAVIOUR OF ADOBE STRUCTURES

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SUMMARY

Most losses of lives and wealth in the developing countries during earthquakes are due to the collapse of adobe houses. In spite of this, after considering different socio-economic reasons and availability of other alternate solutions, it is expected that these types of structures will continue for the decades to come, especially in developing countries. Hence, it is essential to investigate the material properties and numerical modelling techniques of these structures and thereby to ascertain their seismic behaviour. From laboratory tests, it is seen that adobe material reinforced with fiber (straw) has better seismic resistance. Different models have been tested on shaking table for observing the seismic performance of straw reinforced adobe materials. Three dimensional (3-D) FEM is used to simulate the seismic response of the tested models in the shaking test. Both from laboratory and shaking tests, it has been observed that adobe material has non-linearity. The material non-linearity in finite element analysis is considered using the equivalent linearization method. The conditions of the adobe material in the shaking models are different from that of laboratory specimens (e.g., in respect of water content, size, cracks, fabrication etc.). As a result, considerations are necessary to modify the dynamic properties of adobe material, which are obtained from laboratory tests. It is found that the seismic response could be well simulated by using the modified dynamic properties. Based on the simulation, a general methodology has been proposed for predicting the seismic behaviour of adobe structures.

INTRODUCTION

The historical uses of adobe structures are mainly for their many fold advantages such as, low cost, easy availability, easy construction, low energy requirement, and environmental friendliness. Besides, their excellent thermal and acoustic properties makes them appropriate for areas with severe weather condition and high range of temperature variation. This type of structure is common in the developing countries, such as Bangladesh, India, Pakistan, Afghanistan, Iran, Turkey, Peru, and Guatemala. Under favourable weather conditions (in climates of extreme dryness) these earth structures can be extremely durable. But unfortunately these are very vulnerable to earthquake. Araya [1] stated that 90 percent of the population of the developing countries is still living in such buildings. Review of the technical papers points out that

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the collapse of unreinforced masonry and adobe housing caused more than 90 percent of the earthquake fatalities throughout the world [2, 3]. In spite of this, after considering different socio-economic reasons and availability of other alternate solutions, it is expected that these types of structures will continue for the decades to come, especially in developing countries. Hence, it is essential to investigate the material properties and numerical modelling techniques of these structures and thereby to ascertain their seismic behaviour. The behaviour of brittle, unreinforced material, such as adobe is extremely difficult to predict after cracks initiation, even with today's advanced computational capabilities. Nash and Spence [4] described problems and difficulties of the modeling of this type of structures. However, very few efforts were made for numerical modeling of the adobe structures. Again, past earthquakes and Islam and Watanabe [5, 6, 7, 8, 9] showed that adobe material had non-linearity. It suggests that it is necessary to consider the material non-linearity for proper modelling of the adobe structures. If the shaking table test results can be simulated using material properties that are determined from the laboratory tests, a methodology can be developed for predicting the seismic behaviour of adobe structures. Based on the methodology, numerical analysis can be used for predicting the seismic behaviour of adobe structures. Also it is economic and faster than dynamic tests. Several researches were conducted for the numerical analysis of masonry structures such as Page [10]; Karantoni and Fardis [11]; Lotfi and Singh [12]; Mayorca and Meguro [13]. Morales and Delgado [14] have applied modified Distinct Element Method (MDEM) for checking the validity of the construction of two-storey adobe structures. However, these analysis methods cannot be applied directly to the numerical analysis of adobe structures. A few researches have been reported for the finite element (FE) analysis of adobe structures. But those do not consider the effect of material non-linearity. It is worthwhile to check the applicability of the available analytical methods for simulating the seismic behaviour of the adobe structures. The main purposes of the analysis are to check the applicability of the material properties that were determined from the laboratory tests by Islam [15] and the applicability of the FEM to simulate the seismic behaviour. This paper describes the numerical simulation of the seismic behaviour that observed during the shaking table tests of two models M-1 and M-2. Based on the knowledge obtained from simulation, a general methodology has been proposed for predicting the seismic behaviour of adobe structures.

DESCRIPTION OF THE COMPUTER PROGRAM

Equivalent Linearization Method (ELM) is widely applied for taking account of the material non-linearity in the analysis. This approach has been applied by many researches such as Schnabel et al [16], Watanabe and Tochigi [17]. The details of this method are available in many references, such as Kramer [18]. However, the validity of this method for applying in the numerical analysis of adobe structures is yet to appear. In this study, ELM has been used to consider the material non-linearity of adobe in the FEM analysis. A brief description of the computer program is given below. The equation of the dynamic equilibrium is described in Equation 1.

$$[M]\{\ddot{U}\} + [C]\{\dot{U}\} + [K]\{U\} = \{R\} \quad (1)$$

where, [M], [C], and [K] are mass, damping, and the stiffness matrix, respectively. {R} and {U} are the external force and displacement vector, respectively.

Direct integration method has been applied for the response analysis. Newmark-β method has been applied for the integration. For dynamic analysis using direct integration method the damping matrix, [C] requires to be explicitly defined. It is customary to apply Rayleigh damping in which the damping matrix is defined as proportional to mass and stiffness matrix.

$$[C]=\alpha[M]+\beta[K] \tag{2}$$

Where, α and β are the arbitrary constants to be specified.

It is well known that in case of soil structures the value of α and β are not much dependent on the frequency for a certain range. The value of the constants can be taken as follows

$$\alpha = 1.4h\omega_1 \tag{3}$$

$$\beta = 0.6\frac{h}{\omega_1} \tag{4}$$

In Equations 3 and 4, ω_1 is the first predominant frequency of the system and h denotes the damping constant, being defined for the elastic material as the value including both internal and hysteresis damping.

[K] matrix is determined from the stiffness of the material. However, It is well known that stress-strain relationships for soil material are highly dependent on stress conditions. As observed in the current study and in the past earthquakes that shear modulus of adobe material are also dependent on initial stress [6, 15]. Initial stress analysis has been performed for gravity loads only. Mean effective stress is calculated for all the elements. Using the void ratio and mean effective stress for each element, initial shear modulus is determined for all the elements from the Equation 5.

$$G_0 = KF(e)(\sigma'_m)^n \tag{5}$$

Where, K and n are constants for the adobe material, F(e) is a void ratio function and σ_m' is mean effective stress.

Strain dependent shear modulus and the damping of the material is determined from the following relationships as described in Equation 6 and 7.

$$\frac{G}{G_0} = \frac{\gamma_r}{\gamma + \gamma_r} \tag{6}$$

$$\frac{h}{h_{\max}} = \frac{\gamma}{\gamma + \gamma_r} \tag{7}$$

Where, G is the shear modulus at any strain level. G_0 is the initial shear modulus that defined in the Equation 5. γ_r is the reference shear strain. In Equation 7, h and h_{max} are damping at any strain level and maximum damping, respectively.

MATERIAL PROPERTIES FOR NUMERICAL SIMULATION

Shear modulus and damping characteristics of adobe depend on the density, final water content, size of test specimens, and confining pressure [15]. Therefore, it is preferable to determine the necessary material constants for the constitutive relations based on the element tests conducted at the almost same density, and other conditions. However, it is very difficult to make specimens of the similar condition of the material as in the real structures. As a result, there is some deviation in the material properties that determined from the laboratory tests and material in the real structure. Some considerations are necessary to revise the material properties for numerical simulation. $G/G_0 \sim \gamma$ and $h \sim \gamma$ relations are depicted in Figure 1a and 1b, respectively. In Figure 1a and 1b the variation of G/G_0 and h with γ for Hardin and Drnevich [19] model also has been shown. As the condition of the materials in size, water content, length of straw and cracks in the blocks of the model were different from those of the laboratory tests specimens, considerations are made to revise the material properties. Finally, in this analysis, the material constants are determined for each element depending on the confining pressure for each element. Material properties that have been selected for numerical analysis are given in Table 1.

Shear modulus G is given as a product of G_0 (which is a function of confining pressure, σ_m') and a modification factor α as depicted in the Equation 8.

$$G = \alpha \times G_0 \tag{8}$$

$$\alpha = \left(\frac{\omega_1}{\omega_2} \right)^2 \tag{9}$$

Where ω_2 is the primary natural frequency obtained from the eigen value analysis with initial shear modulus, G_0 and ω_1 is the resonance frequency obtained from the resonance curve of the experiment. Equation 9 means that the dynamic properties of adobe are modified to produce a resonance state in the numerical simulation with the sinusoidal excitation of frequency ω_1. The modification factor α depends on the several parameters that make difference in the material of the laboratory specimen and in the structure. If the factor α can be determined directly, quantifying the effects of the factors, material properties can be calibrated directly. Similar, modification factor α had been also used by Ohshima and Watanabe [20]. The relationship between G_0, G/G_0, and γ_r for the adobe material with 0.50% straw content are described in the equations 10, 11, and 12.

$$G_0 = 954 \frac{(2.97 - e)^2}{(1 + e)} \left(\sigma_m{}' \right)^{0.52} \tag{10}$$

$$\frac{G}{G_0} = \frac{\gamma_r}{\gamma + \gamma_r} \tag{11}$$

$$\gamma_r = 3.5 * 10^{-3} \tag{12}$$

Where, γ_r is reference shear strain.

Table 1. Material properties for numerical simulation

Properties	Value	Unit
Shear modulus, G	$G = \alpha \times G_0$	
Poisson's ratio	0.22	
Dry density	1.04	gm/cm^3
Cohesion	130.0	KN/m^2
Friction angle	35	deg.
Damping constant	$h = 0.30 \frac{\gamma}{\gamma + \gamma_r} + h_{initial}$	

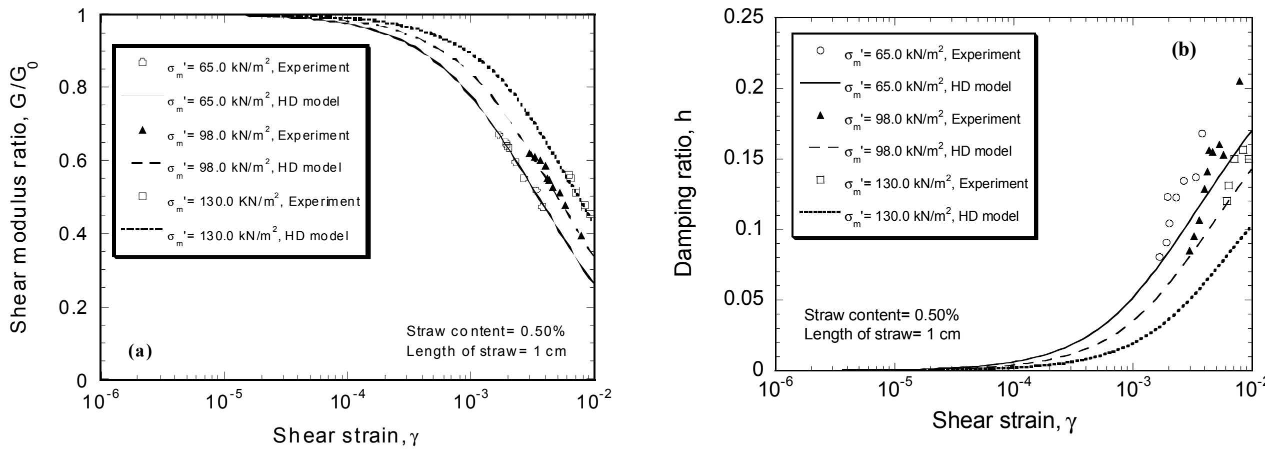

Figure 1. (a) $G/G_0 \sim \gamma$ and (b) $h \sim \gamma$ relationships for adobe material.

Damping constant, h is determined from the laboratory test data. It is seen from Figure 1b that in the initial strain range from 10^{-6} to 10^{-4}, damping ratio, h is zero, which might not be true as observed in the test results of other investigations such as, Ishida et. al. [21]. In the material test program, material properties in the low strain could not be determined by the method applied. This might be reason for the deviation. This recommends the use of resonant column test. However, by trail in the FEM the initial damping value for this strain range was set at 0.02 to 0.04. As seen from the Figure 1b, the h_{max} is 0.23, but it is necessary to increase the h_{max} to 0.30. As discussed earlier, several factors affect the models due to which the damping was increased. The following Equation 13 is used for damping ratio, h.

$$h = 0.30\frac{\gamma}{\gamma + \gamma_r} + h_{initial} \qquad (13)$$

where, γ_r is $3.5*10^{-3}$ and $h_{initial}$ is 0.02 ~ 0.04.

NUMERICAL SIMULATION

Using the material properties and the procedure that has been described in the preceding sections numerical analysis has been performed by 3-D FEM. Numerical simulation has been performed for two models that have been tested under shaking load. However, each model was exited for three cases by changing the amplitude of accelerations, i.e., 50 Gal, 100 Gal and 200 Gal. During shaking test, separation between blocks and mortar has been observed for both the models for 100 Gal and 200 Gal cases. Here, the analysis has been performed only for the first case, i.e., for the 50 Gal case only. For other cases suitable interface element may be used for considering the separation of the models. More details about the shaking models are available in Islam and Watanabe [8] and Islam [15].

Simulation of model M-1

Figure 2 shows the FEM idealization of the model M-1. The height of the model is 1.0 m, which consists of 10 blocks. Mortar was applied to join the blocks in between two blocks. Mortar joint has been neglected while modeling the shaking model. 20-nodded solid elements have been used to incorporate the blocks. Each element has the dimension of 0.25 m × 0.50 m × 0.10 m.

Initial stress and modal analysis

Initial stress analysis has been performed for the model M-1 only for gravity load. Mean effective stress has been calculated as the average of the three stresses in the three directions for each element. Using the initial shear modulus for all the elements modal analysis is performed for the model M-1. First predominant frequency determined from the eigen value analysis is 11.92 Hz. However, the first predominant frequency for the model in the shaking test is 6.1 Hz. Therefore, the dynamic properties that were determined from the laboratory tests has been reduced by multiplying a factor $\alpha=(6.1/11.92)^2=0.262$ to obtain the resonance condition of the model that was observed in the shaking. Using the reduced dynamic properties, the first predominant frequency is 6.4 Hz, which is very close to that of shaking test. This reduced property is used in the numerical analysis. Here, it is to be noted that the factor α can be determined directly through extensive laboratory efforts. Mode shapes (first and second) of the model from eigen value analysis are given in Figure 3.

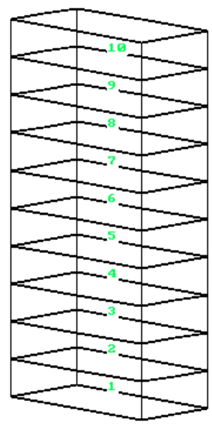

Figure 2. FEM idealization of model M-1.

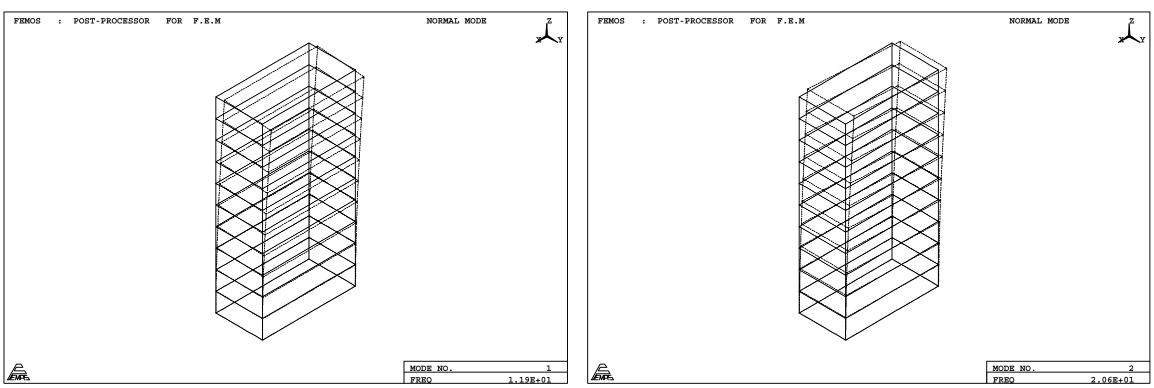

Figure 3. Mode shapes of model M-1 (a) first mode and (b) second mode.

Acceleration time histories of base motion

From the shaking table test it was seen that the first predominant frequency of the model is 6.1 Hz. The acceleration time history that had been used as the input motion for 6.1 Hz for the model M-1 during shaking test is given in the Figure 4. The exactly same base motion that was provided in the shaking test is used as the input base motion in the numerical analysis.

Comparison of acceleration time histories

Acceleration time histories that observed in the shaking test (to the shaking direction) at the mid-height and top of the model M-1 are compared with that obtained from FEM in Figure 5. The results of FE analysis are well coincident with the experimental one in respect of both the phase and amplitude.

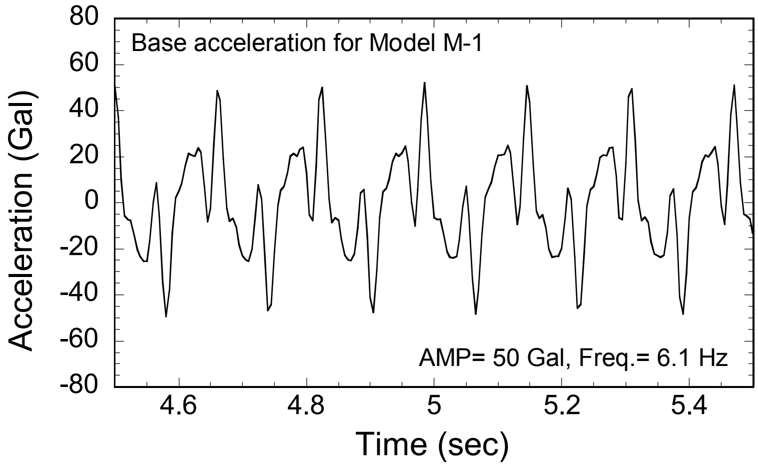

Figure 4. Base acceleration for the model M-1.

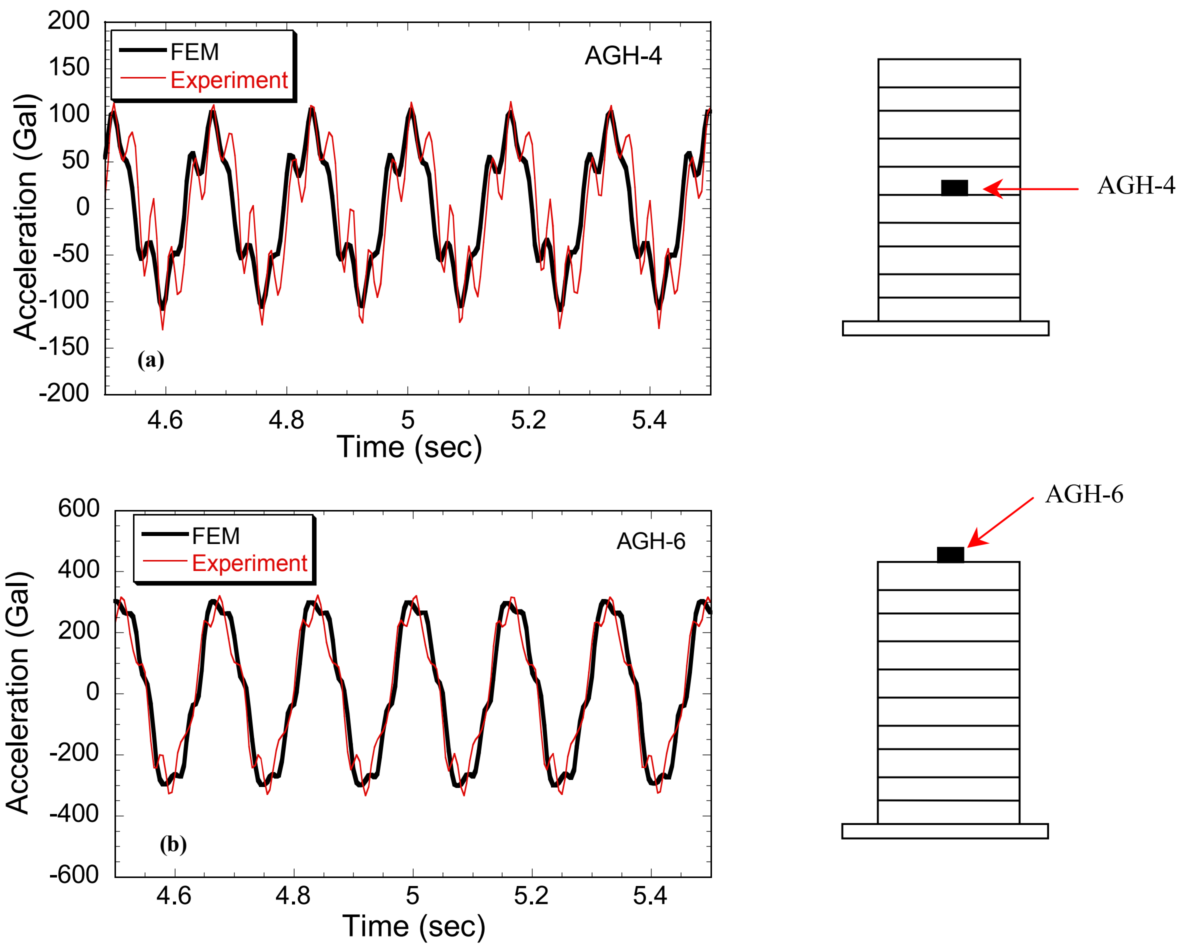

Figure 5. Acceleration time histories at (a) mid-height, (b) top of the model M-1.

It means that Equivalent Linearization Method (ELM) can be applied successfully for simulating the seismic response of adobe structures before failure occurs. It also implies that the dynamic properties that were determined from the uniaxial cyclic loading test can also be applied considering the factors that affect the material properties. However, more investigations are necessary to quantify the factors for calibrating the material properties.

Comparison of displacement time histories

Relative displacement time histories of the model M-1 by FEM and that from shaking tests are compared in the Figure 6 for mid-height and the top of the model, respectively. It is seen that the coincidence of the displacement time histories for FE and the experiment is very good in respect of both the amplitude and phase angle. Therefore, it can be concluded that using the ELM seismic behaviour that is observed in the shaking test can be well simulated.

Maximum relative displacement from the Finite Element analysis and shaking test with the height from the base of the model M-1 are compared in the Figure 7. It is seen that there is very good agreement for the displacement along the height of the model for FEM and experiment.

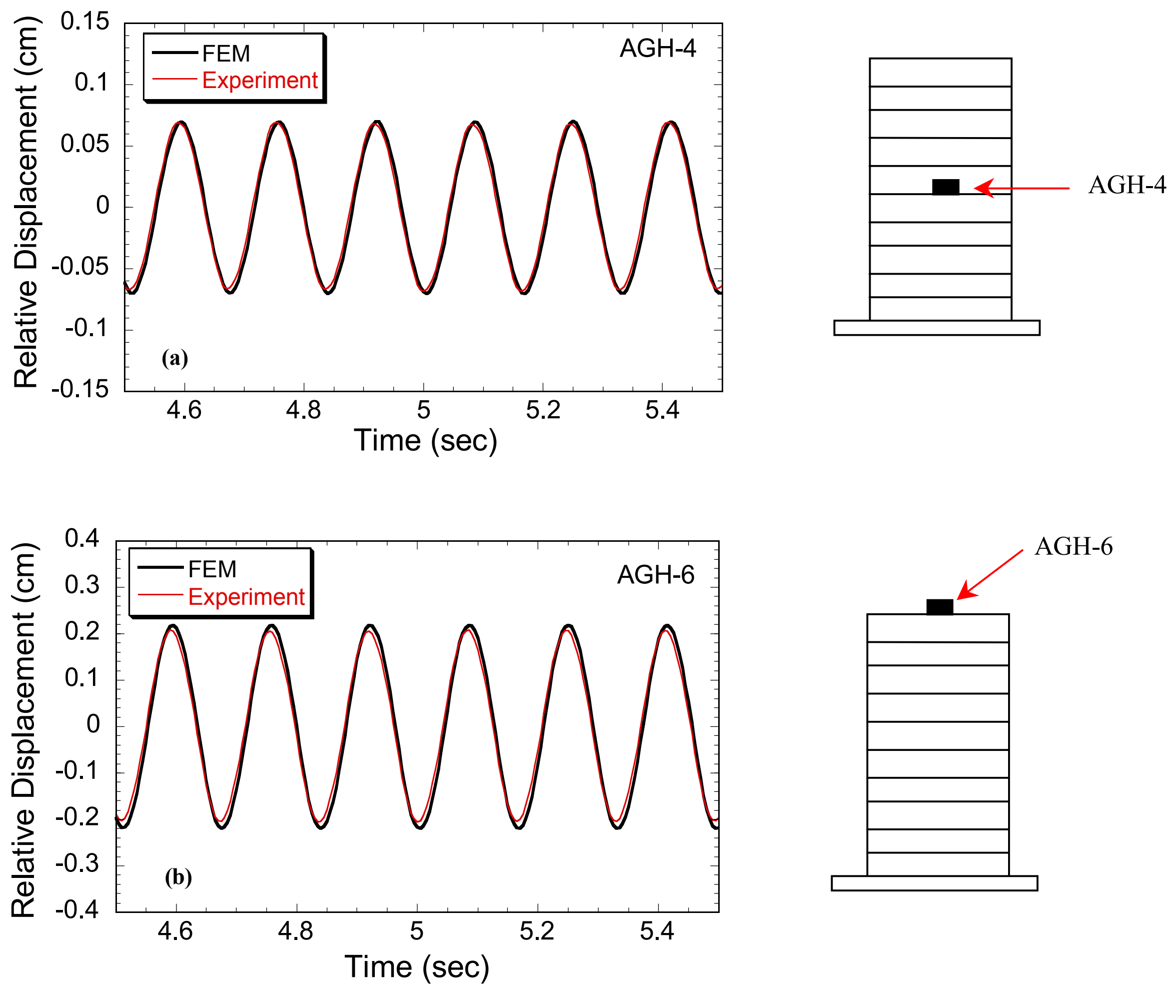

Figure 6. Displacement time histories at (a) mid-height and (b) top of the model M-1.

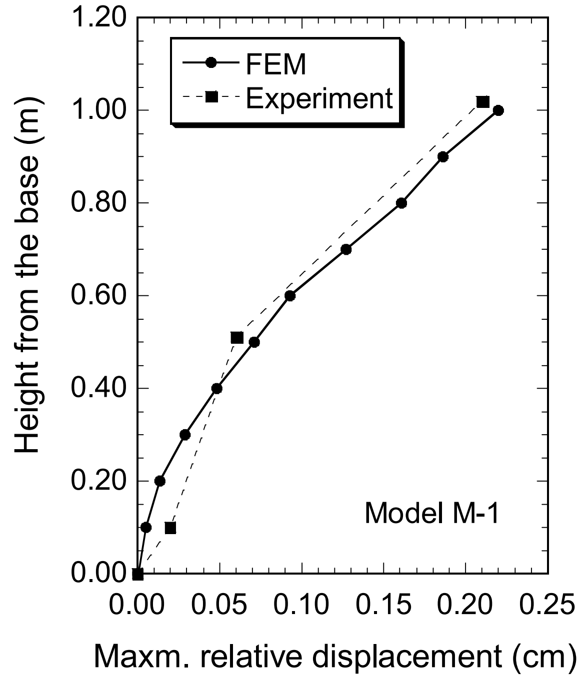

Figure 7. Displacement along the height of the model M-1.

Simulation of model M-2

Numerical simulation is performed for the model M-2 also in accordance with the same procedure that has been described in the previous section. In Figure 8, mesh of the model M-2 is shown. This model has joints in both the horizontal and vertical directions. But the joints has been neglected in the FEM modeliing since no speration has been observed during this case of shaking. In this case also numerical simulation has been performed for the resonance frequency that has been observed in the shaking test. The first predominant frequency that was observed in the shaking test of this model is 5.0 Hz.

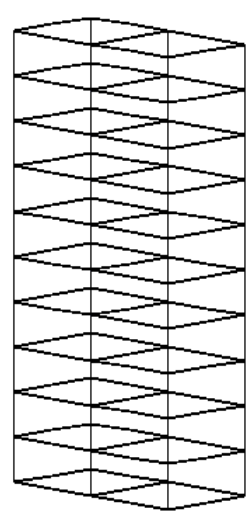

Figure 8. FEM idealization of model M-2.

Initial stress and modal analysis

Initial stress analysis has also been performed for the model M-2. Mean effective stress is calculated from the initial stress analysis. Initial shear modulus for all the elements has been calculated based on the initial stress in the elements. Using the initial shear modulus, eigen value analysis has been performed for the model. First predominant frequency of the model is 10.3 Hz from eigen value analysis. However, the first predominant frequency that was observed in the shaking test is 5.0 Hz for the model. Therefore, dynamic properties have been reduced with the factor α= 0.235. With the reduced dynamic properties, the modal analysis is performed again. With the reduced property, the first predominant frequency is 4.98 Hz, which is very close to the first predominant frequency that was observed in the shaking test for this model. First and second mode shapes of the model are given in Figure 9.

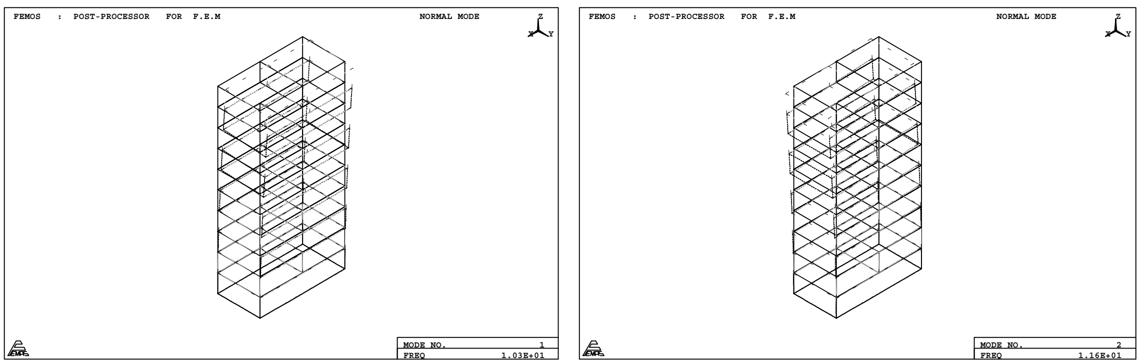

Figure 9. Mode shapes of the model M-2 (a) first mode and (b) second mode.

Acceleration time history of the base motion

The acceleration time history that has been observed at the resonant frequency during the shaking test is being used as the input base motion for the analysis. The acceleration time history that has been used for base motion during shaking test of this model is presented in the Figure 10. The frequency of the base motion is 5.0 Hz (first predominant frequency from shaking table test of this model).

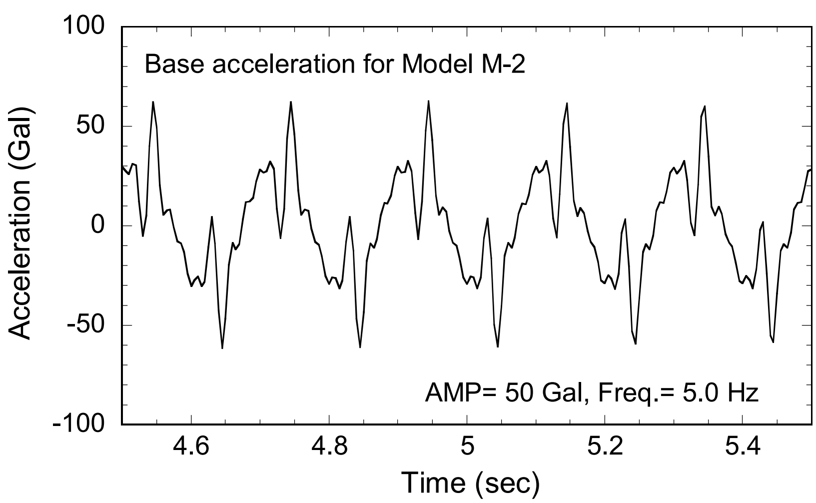

Figure 10. Acceleration time history of the base motion for model M-2.

Comparison of acceleration time histories

Acceleration time histories that observed in the shaking test at the mid-height and top of the model M-2 are compared with that obtained from FEM in Figure 11. The FEM analysis results are in conformity with the experimental one in respect of both the phase and amplitude. It means that ELM can be applied successfully for simulating the seismic response of adobe structures before failure occurs. It also implies that the dynamic properties that were determined from the uniaxial cyclic loading test can also be applied with considering the factors that affect the material properties. However, to quantify the effects of each factor it needs many investigations by varying the condition of the model during test.

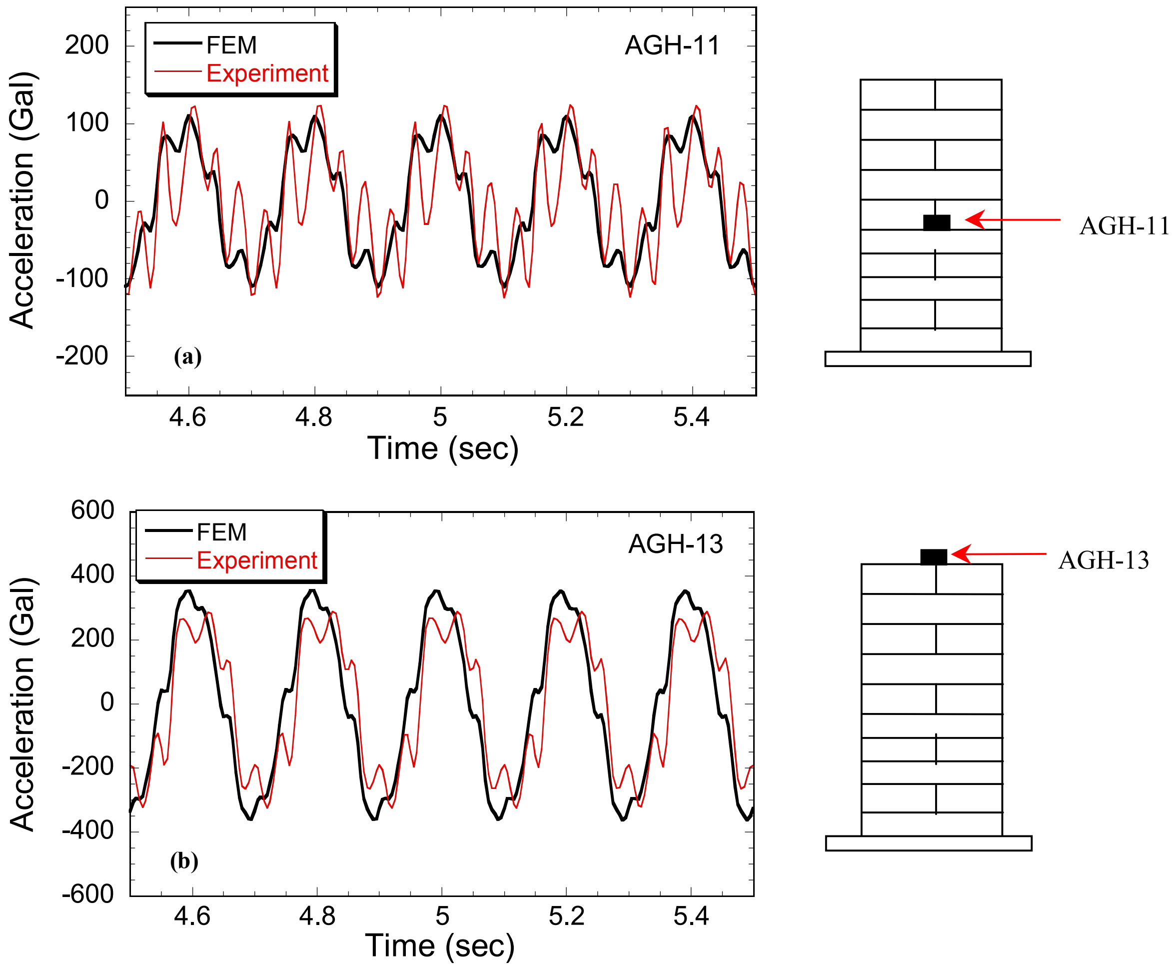

Figure 11. Acceleration time histories at (a) mid-height and (b) at the top of the model M-2

Comparison of displacement time histories

Relative displacement time histories of the model M-2 by FEM and that from shaking tests is compared in the Figure 12 at the mid-height and for the top of the model, respectively. It is seen that the coincidence of the displacement time histories for FE and the experiment is very good in respect of both the amplitude and phase angle. Therefore, it can be concluded that using the ELM seismic, behaviour that is observed in the shaking test can be well simulated by FEM. Maximum relative displacement that observed in the shaking test along the height of the model has been compared with that of the FEM and shown in Figure 13. It is seen that there is a very good agreement between the calculated and the observed one.

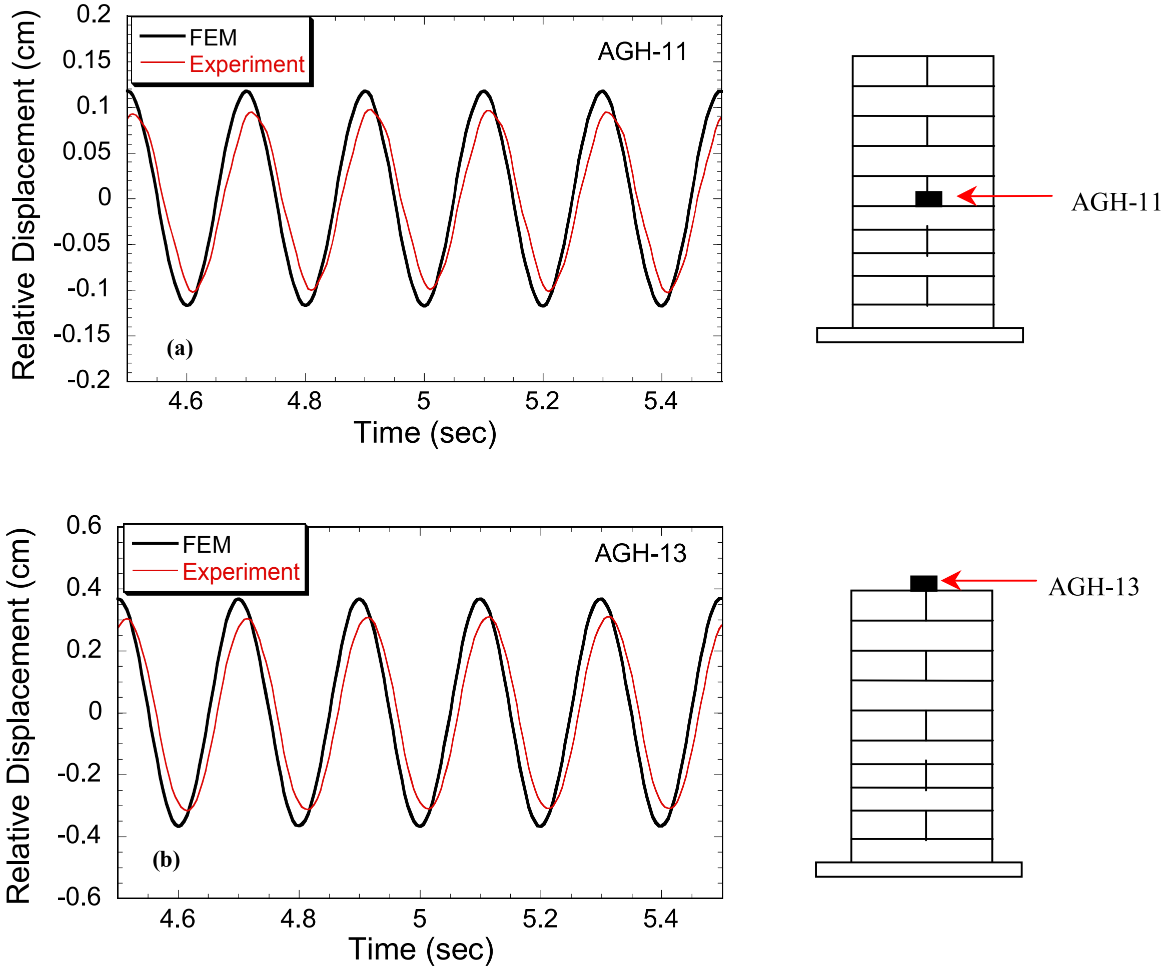

Figure 12. Displacement time histories at (a) mid-height and (b) top of the model M-2.

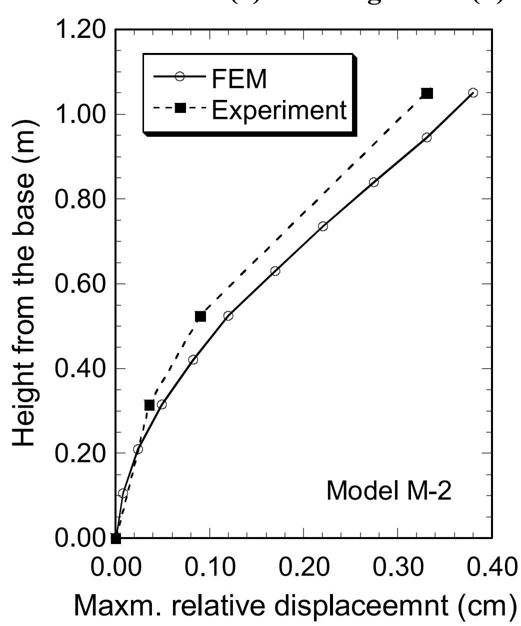

Figure 13. Displacement along the height of the model M-2.

METHODOLOGY FOR NUMERICAL ANALYSIS

In the preceding sections, numerical simulation of the models is described. It is seen that the seismic behaviour that was observed in the shaking test for the Case I, i.e., for 50 Gal case can be well simulated using the material properties that was obtained in the material test program. However, it is necessary to consider some factors that make difference in the condition of the material in the laboratory specimens and in the real structures. Based on the knowledge of material tests (both static and dynamic), shaking table test and numerical simulation, a methodology has been proposed. The proposed methodology is that both the laboratory and model tests are necessary for predicting the seismic behaviour of adobe structures. However, the difference in the material condition may be mainly due to the difference in water content. Since the water content of the adobe specimens were in the range of 8 to 10% while the water content of the adobe blocks of the shaking models were in the range of 25 to 30%. If the effect of the water content can be directly determined, the modification factor α might be determined directly. For the analysis of real structures, at first the water content of the structure is to be determined and then, according to that water content, material test should be performed.

CONCLUSIONS

Numerical simulation is performed for two models that were tested under sinusoidal load using the material properties that determined from the laboratory tests. From this knowledge, the following conclusions can be drawn.

The seismic behaviour of adobe models that was observed in the shaking test can be well simulated using the dynamic properties that were determined from uniaxial cyclic loading test in the current study. FEM is applicable for predicting seismic behaviour of the adobe material.

Equivalent Linearization Method is applicable for the numerical simulation of the adobe structures to consider the material non-linearity.

Some considerations are necessary to revise the material properties due to the difference in the material conditions of the laboratory specimens and material in the real structures, such as the difference in the water content, cracks in the blocks, cracks in the mortar, straw length, fabrication of the model, drying process, etc. However, lots of investigations are necessary to quantify the effects.

Numerical simulation of the seismic response of the two models revealed that some initial value (low strain level) of damping is necessary for the proper modelling of the adobe material.

General methodology has been proposed for predicting the seismic behaviour of adobe structures. Both the material and model tests are necessary for predicting the seismic behaviour. This methodology can be used for predicting the seismic behaviour of the real adobe structures.

In this study the numerical analysis is performed for the case before separation has been occurred. Using suitable interface element the other cases may be simulated.

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