Dynamic Analysis of Historical Brick Masonry House

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Abstract: Brick masonry constructions are very common in many areas in the world and their failure in earthquakes has been the cause of many deaths. Since human safety is main issue of disaster management, people are more concerned about the structural assessment and strengthening of those constructions. One historical brick masonry house located in Kathmandu world heritage site is modeled by FEM (finite element method) and analyzed in El Centro earthquake ground motions. Bricks are modeled as solid elements and the interfaces between the brick units are modeled as zero thickness joint elements. Then, non-linear analyses of the house are applied satisfying the famous Mohr-Coulomb failure criterion. The result shows that the house is very weak and sustains large deformation in El Centro 1940 Earthquake. A strengthening solution modifying the connections of existing elements and adding wooden frame inside the house can reduce the deformations significantly.

Key words: Solid element, joint element, strengthening, FEM, brick masonry, dynamic analysis.

1. Introduction

Brick made temples, royal palaces and residential houses with beautiful architectural appearances are main identity of Kathmandu Valley. It was constructed in Malla period probably 300 years ago and has become one of the main sources of tourist attractions since then. Historical records tell that many earthquakes have occurred in it or its vicinity. History of earthquakes has been described since enlightenment of Buddha 538 BC. Details of earthquake occurrences and damages have been described since 1223 [1]. Big earthquakes hit the Kathmandu Valley in 1255 and 1344 which killed one third of the population at that time and damaged many temples and houses. Since then, many earthquakes have been reported and the most damaging one is 1934’s Nepal Bihar Earthquake. More than 10,000 people were killed in 1934 earthquake which is the biggest earthquake described in the Nepalese literatures [2]. Recently, occurrence of great earthquake has been revealed in 1408 which had damaged 500 km of Himalaya [3]. If the ages of masonry temples and history of earthquakes is compared, most of the historical temples should have passed through severe earthquake ground motions. They should have sustained damages and later renovated. From this evidence, we can see some earthquake resistance techniques such as square shaped buildings, use of wooden elements along the wall to discontinue vertical joints. However, these simple techniques used without proper knowledge of where and how to use are not sufficient to resist severe earthquake motion which is expected to come soon. Thus, strengthening of these houses against probable earthquake is most important task of risk management. A historical masonry house (so-called Lalitapur house in Fig. 1) located in Lalitpur sub-metropolitan city, Kathmandu, is analyzed giving El Centro 1940 earthquake ground motion history input which is described in detail in the following sections.

2. Description of Numerical Methodology

Masonry behaves distinct directional properties due to the interfaces between the elements. The large number of influence factors such as interior voids, anisotropy of bricks, dimension of bricks and joints, arrangement of bed and head joints and quality of
workmanship make the numerical modeling of masonry very complex. Limited numbers of variables that are used in the numerical model can not catch the actual behavior of brick walls due to its varieties of properties. Basically, two methods, first, DEM (distinct element method) which considers the brick units as non-deformable solids and their movements are evaluated through equations of motions and other, second, FEM, are used for analyzing masonry houses. FEM ranging from very simple method such as considering masonry as single phase material, to very complex method such as considering each element and joint separately, have been widely used and well accepted tool.

FEM has been used in the field of rock mechanics by Zienkiewicz et al. [4] since 1970. Recently, this concept has been also used in brick masonry by Tzamtzis and Nath [5], and Tzamtzis and Asteris [6] to simulate time dependent sliding and separation along mortar joints. Three dimensional finite element models were formulated by considering the relative displacements between the top and the bottom of the base elements and constitutive relationship based on material properties containing shear and normal stiffness which can be found from stress displacement curves of mortar. A brick masonry wall was analyzed in static and dynamic loadings and found capable to predict appropriate response. Using similar approaches, Lourenco et al. [7] and Senthivel et al. [8] investigated on dry joint cut sawn stone masonry walls to verify the experimental investigations. This concept has also been applied to investigate the effectiveness of wooden bond beams in dry stone masonry houses [9]. Thus similar idea of modeling the brick units as solid elements and interfaces between them as zero thickness joint elements is employed here. However, there are large numbers of bricks in a house and modeling of each brick separately is very complex and impossible. Thus simplified numerical model is developed making equivalent eight node elastic solid elements for brick wall blocks and eight node joint elements for interfaces between stones as shown in Fig. 2. In Fig. 2, \(x, y \) and \(z\) are global axes and \(\xi, \eta \) and \(\zeta\) are local axes. Ultimate objective of dynamic analysis is to solve the widely known equation of motion as shown in Eq. (1):

\[
[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = -[M]\{\ddot{u}_g\} 
\]

where, \([M]\), \([C]\) and \([K]\) are mass, damping and stiffness matrices, \(\{\ddot{u}\}, \{\dot{u}\}\) and \(\{u\}\) are acceleration, velocity and displacement responses, respectively. And \(\{\ddot{u}_g\}\) is input ground acceleration. The stiffness matrix for the system is obtained assembling individual solid and joint element matrices. Formulation of stiffness matrix for solid element is refereed to Chandrapatla and Belgundu [10]. The displacement of joint element
depends upon relative movement of top and bottom solid elements (Fig. 2), and corresponding stiffness matrix for zero thickness joint elements is given in Eqs. (2) and (3) as formulated by Tzamtzis and Nath [4-7]:

\[
[K] = \int_1 \int_1 [N]^T [k][N] \det[J] \xi \eta d\xi d\eta
\]

(2)

\[
[k] = \begin{bmatrix}
k_{xx} & 0 & 0 \\
0 & k_{yy} & 0 \\
0 & 0 & k_{nn}
\end{bmatrix}
\]

(3)

where, \(k_{xx}, k_{yy}\) and \(k_{nn}\) are components (shear stiffness along x direction, shear stiffness along y direction and normal stiffness) of material property matrix \([k]\) of joint, \([N]\) and \([J]\) are shape function, and Jacobian matrices, and \(\xi\) and \(\eta\) are local coordinates. Normal and shear stiffness are calculated considering the wall as series of two vertical springs, one representing by the stone unit and other representing by joint following Lourenco et al. [7] which leads the Eqs. (4) and (5):

\[
k_n = \frac{1}{h} \left( \frac{1}{E_{wall}} - \frac{1}{E_{unit}} \right)
\]

(4)

\[
k_s = \frac{k_n}{2(1+\nu)}
\]

(5)

where, \(k_n\) is normal stiffness of joint, \(k_s\) is shear stiffness of joint, \(h\) is height of element, \(E_{wall}\) is Young’s modulus of elasticity of wall, \(E_{unit}\) is Young’s modulus of elasticity of brick unit, and \(\nu\) is Poisson’s ratio. In order to get damping matrix (Eq. (6)), mass and stiffness proportional Rayleigh damping is used:

\[
[C] = \alpha[M] + \beta[K]
\]

(6)

where, \(\alpha\) and \(\beta\) are coefficients selected to control the damping ratios of the lowest and highest modes expected to contribute significantly to the response.

2.1 Parameters

Material properties such as modulus of elasticity for wall, coefficient of friction, cohesion, Rayleigh damping coefficients are necessary. No exact values for these parameters have been reported in the literatures. Among them, modulus of elasticity is the most important parameter on the basis which stiffness matrices for solid and joint elements are formed. Thus, a non-destructive testing technique using acoustic wave emission was done. Then shear wave velocities for single brick and for wall were found to be 1,530 m/s. and 410 m/s, respectively. Unit weight and coefficient of friction were measured 19 kN/m³ and 0.3, respectively. Cohesion is taken zero. The stiffness constants for shear and normal were calculated by using Eqs. (4) and (5). The concept of joint element is to represent the non-linear behavior of the adjacent elements. The model has elements with varying thickness thus separate values of coefficients are required depending upon their depth. However, in this study, an average value of depth 25 cm has been taken and corresponding values of normal and shear stiffness coefficients are \(3.4 \times 10^6\) kN/m³ and \(1.4 \times 10^6\) kN/m³, respectively. Unit weight and modulus of elasticity for wooden elements are \(4.47\) kN/m³ and \(8.1 \times 10^6\) kN/m², respectively. Regarding damping, very limited information is available in linear solid mechanics problem, and even very less information is available in non-linear dynamic analysis. For problem under consideration, the coefficients are \(\alpha = 0.0174\) and \(\beta = 0.172\) are taken maintaining damping approximately 3% following Wakai and Ugai [11].

2.2 Constitutive Relationship

The joint is characterized by fully elastic-perfectly plastic and incapable of taking any tensile forces. The idealized constitutive relationship shown in Fig. 3 is used to take the sliding and opening of joint. Separation occurs when the normal strain is greater than zero because joint can not take any tensile stress and both normal, and shear stiffness are set to zero. Contact occurs when normal strain is less than zero, and normal forces will restore according to normal stiffness of joint. In Fig. 3, \(\tau_y\) is yield shear stress, \(\sigma_n\) is normal stress; \(\varepsilon_s\) is yield shear strain and; \(\varepsilon_n\) is normal strain. Sliding occurs when the shear at joints exceeds value given by Mohr-Coulomb yield criterion:
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\[ \tau_y = c + \sigma_n \tan \phi \quad (7) \]

where, \( c \) is cohesion (assumed equal to zero) and \( \tan \phi \) is coefficient of friction.

3. Description of Model House

The historical brick masonry house (Fig. 1) located in Lalitpur Municipality of Kathmandu City, is modeled by finite element method as explained just before. The house (Fig. 1) is two storeyed, 16.5 m in length and 5.6 m in width. Wall is made of traditional brick with thickness of 60 cm at bottom and 50 cm at top tapering slightly from bottom to top. Thus for analysis, average thickness of 55 cm is taken. It was constructed 300 years ago. It sustained damages in earthquakes and repaired many times. Recently, its original roof has been replaced by corrugated galvanized iron sheet which rests over wooden plans and battens and wall interior has been plastered by cement sand mortar. The floor has been recently replaced by concrete which rests over wooden boards supported by planks and beams. Now, it looks like completely repaired hiding its original construction and has been using as public purpose. The building has very large opening in the front side. Wooden posts are supporting the wall of upper storey. In the upper storey, there is big wooden window placed at mid span of wall, which is slightly projected outside showing nice aesthetic view. Thus separate modeling of walls, floor and roof, and their component-bricks, windows, doors, posts are extremely complicated job. Thus, wall is discretized into small numbers of solid brick elements, vertical post are modeled as wooden solid and the big window place in the front side of upper storey is model as solid elements. Total solid elements are 2,995, solids are 1,189 and joint elements are 1,809.

4. Conclusions

Since the wooden elements and bricks are inter-connected at floor and roof levels, they behave like rigid floor diaphragm. If these elements are considered separately, the model becomes very completed. Thus the masses are lumped at wall where the floor and roof rest. Separate color can be observed in the model (Fig. 4a). During lateral loadings, floor acts rigidly and the corresponding solid elements at floor and roofs are assigned rigid with same material properties. Joint elements are provided to connect the floors with walls. Total loads of floor and roofing was calculated 1.5 kN/m². Then, static analysis was applied for vertical loads and self weights. And obtained stresses were used in dynamic analysis as initial stresses. In second step, using El Centro 1940 Earthquake as example, dynamic analysis was done. Equation of motions (Eq. (1)) was evaluated at 0.01 interval of time by New Mark’s beta method considering the constitutive relationship shown in Fig. 3. Since the residual forces obtained from deducting
Fig. 4  FEM model and its behavior in earthquakes in existing condition: (a) simplified FEM model; (b) response in El Centro 1940 Earthquake (unit in m).

Fig. 5  FEM model and its behavior in earthquakes after applying strengthening measures: (a) wooden beam and column added model; (b) response in El Centro 1940 Earthquake.

actual force developed and permissible force calculated from constitutive relationship produce non-linear deformation at the joints which are evaluated by Newton Raphson method, in full three dimensional analyses, there is possibility of obtaining tensile and compressive forces right from the beginning. So, the house experiences tension at some areas likely near openings and at other weak zones which go on iteration and find non-linear deformation. If the residual forces are big, iteration takes very long time and ultimately computation becomes very lengthy. Thus a ceiling with 30-cm displacement has been set in the program. In the brick masonry, if the displacement exceeds 30 cm, it is supposed to be unstable and analysis beyond this value might be meaningless and just taking time only. Normal length of brick is 23 cm, and, if its deformation is 30 cm, it completely dislocates by its original position. However, it is arbitrarily assumed value and one can take its own definition and value. The purpose of termination of analysis is just to save time only. The model house experienced more than 30-cm displacements when the analysis reaches 9 s. The deformations are shown in Fig. 4b. The deformations of elements are shown in different colors. The maximum displacement is 27 cm. The reason why there is only 27-cm displacement shown in Fig. 4b, while it was set 30 cm in the numerical model, is the output was written only after 10 steps. Since El-Centro 1940 Earthquake is first recorded earthquake and 40% houses have been damaged, it is quite reasonable to say that this brick masonry house...
sustains very large cracks and deformations and cannot survive.

Being historical house, it has heritage value and should be protected against future earthquake. There are many methods that can be used for strengthening of traditional houses using various materials such as FRP (fiber reinforced polymer), steel in various forms such as beams, columns, meshes, etc., PP (poly-propylene) bands, woods, etc. However, archeologists and conservationists do not allow intrusion by all kind materials such as concrete, steel, FRPs, etc. Thus, there are very few options remaining, for example, addition of wooden beams and column internally could be one of the possible options. Thus, looking at the weak zones, near the openings and top of shorter walls, as strengthening measures, joints between the wooden posts are made fixed, the floor elements are made connected with the wooden frame placed around the openings, and wooden beam and columns as shown in Fig. 5a are added. Then, the house is analyzed again in the same earthquake ground motion. During full cycles of analysis, it gets maximum displacement 3.4 cm (Fig. 5b). It shows that simple method of strengthening can contribute significant strength and reduce the large deformation. Being old brick masonry, the wall is already stressed and propagation of crack is obvious even in small deformations. Though it might not be serviceable after earthquake, it may protect the lives. And also, wood is easily available in local areas and easily acceptable by the heritage conservation community.

References


