COLLAPSE MECHANISMS AND SIMPLISTIC SEISMIC EVALUATION OF NON-ENGINEERED BRICK MASONRY HOUSES

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ABSTRACT :

Masonry buildings usually occupy a major percentage of the construction type in many developing countries. Unfortunately, most of these buildings are either weak against earthquakes or severely deteriorated over the structure's lifetime. Due to the large number of existing masonry buildings, a fast screening and objective evaluation tool is necessary. This study attempts to identify the major structural vulnerabilities of masonry buildings depending on the floor system and wall properties. A reinforced concrete floor would enable rigid diaphragm behavior while wooden logs placed to support commonly heavy earthen roofs generally concentrate vertical and horizontal loads on the two supporting and parallel walls that logs are supported. In-plane and out-of-plane capacities of the walls and load demands were calculated using linear analysis and ultimate state failure patterns assuming the failure will be brittle beyond the linear range. Vulnerability assessment was conducted using a macro based spread sheet program, which may also be utilized by survey engineers or technicians using mobile tablet PCs. Visual inspection results were also incorporated for apparent degradation of aging masonry buildings although doing so would add a certain level of subjectivity. An example was provided to demonstrate the use of evaluation strategy.

KEYWORDS: Masonry, seismic, evaluation, collapse, mechanism

1. INTRODUCTION

Existing masonry house stock in developing countries is a major concern especially if the houses are located on seismically active zones and were built without engineering services. According to Turkish Statistical Institute (TUIK) census 2000 data, about 51% of the existing building stock in Turkey is masonry type. More than 90% of Turkey's population and surface area are under seismic risk. Non-engineered masonry houses remain to be a source of concern in countries similar to Turkey. Engineers are finding economical and simple ways to strengthen houses located at technologically challenged areas (Turer and Golalmis, Turer and Ozden, Turer et.al.); however, understanding collapse mechanisms and finding simple methods to evaluate masonry houses is the first important step in order to prioritize the neediest houses as well as choosing the right strengthening methods. This study makes an attempt to explain simple collapse mechanisms as well as defining simple equations to quickly evaluate common collapse mechanisms to find governing failure modes of masonry. A spreadsheet based evaluation program utilizing macros was suggested to quickly analyze masonry houses on the field by using a tablet PC. The effect of vertical loading on the horizontal load capacity of walls was elaborated. Finally, an example house was evaluated for demonstration purposes.

2. COMMON COLLAPSE MECHANISMS OF MASONRY HOUSES

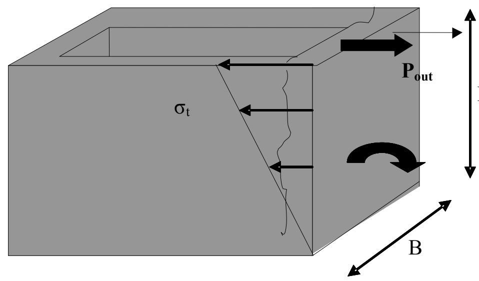
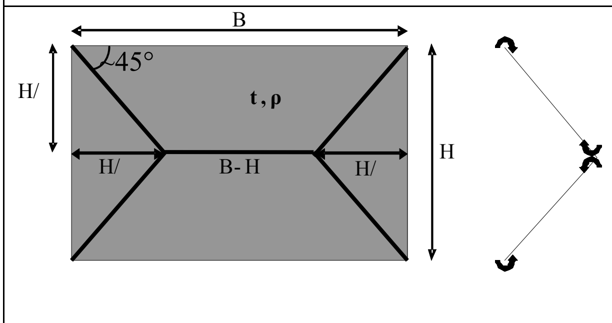
Failure modes of masonry houses depends on numerous parameters; the most important ones being the number of storeys, existence and frequency of window and door openings, strength – quality of the building blocks (e.g., bricks, adobe, stones) and mortar between building blocks, wall thickness, aspect ratio (length versus height) of the walls, existence and frequency of lintels, number and intervals of orthogonal walls supporting other walls in the out-of-bending direction, interlocking level of the walls that are perpendicular to each other (especially at the corners), slab and roof type, weight and mass of the house, footing and soil conditions, seismicity of the region, and closeness to the fault lines. The most common failure modes of masonry walls may be separated to two main categories as the "in-plane" and "out-of-plane" failure. The in-plane modes can be itemized as a) diagonal shear cracking, b) horizontal cracking at the top and bottom of the wall due to rigid-body rocking motions of the wall, and c) a single horizontal cracking that would cause shear failure. The out-of-plane failure is mostly dominated when walls are not supported at the ceiling level or not supported by orthogonal walls for considerable distances. Alternatively, the walls may fail in a bursting mode in out-of-plane direction if the wall is supported at all sides but too thin to keep itself intact. The existence of a rigid diaphragm over walls by means of a concrete floor is very important to restrain the top edges of walls in out-of-plane direction as well as distribute inertial forces to walls in their strong in-plane directions. Often times, the floors and roof are built using wooden logs or beams that only sit on two opposing and parallel walls. In that case, the inertial forces at the floor level are distributed to the two supporting walls in their weak and strong directions; however, the governing failure mode is always the weak out-of-plane bending direction. Such a one-way slab floor would also do a poor job in restraining the other (non-supporting) walls at the floor level, leaving them vulnerable to out-of-plane bending failure. Failure modes summarized above are discussed in detail under each sub-heading below; simple assessment equations are provided for each relevant section.

2.1. Out-of-plane failure of the walls

It is important to note that the out-of-plane failure of walls may also be triggered by in-plane failure of walls, or vice versa. A diagonally cracked wall can easily be lost with minor shaking in the out-of-plane direction or a wall cracked in out-of-plane bending direction may not be capable of carrying any load in the in-plane direction. Therefore, the minimum load that would cause failure of walls in either direction may be accepted as the capacity of the wall that will lead to failure. Exceedance of the linear range for unreinforced masonry (URM) walls can be assumed as failure as the URM walls are commonly accepted to have brittle behavior and no reserved strength after cracking.

The most important parameters that affect the out-of-plane bending capacity are a) the aspect ratio between the wall length and height, b) existence of ceiling restraining the upper edge of the wall, c) thickness, d) vertical force acting on the wall, and e) strength of the material in tension and compression. The critical out-of-plane failure modes and governing equations are listed in Table 3.1.

Table 3.1 Data for beams under dynamic loading

	$P_{out} = \left(\frac{mass_{ceiling}}{2} + \frac{mass_{wall}}{2}\right) \times accel$ $\sigma_t \times \frac{H \times t \times N}{2} \times \frac{2 \times H}{3} \geq P_{out} \times H$ $\sigma_t \times \frac{t \times N \times H}{3} \geq P_{out}$
	$\omega_{out} = 1m^2 \times t \times \rho_w \times a_o$ $\sigma_t = \frac{\omega_{out} \times H^2 \times (3B - H)}{8 \times t^2 \times (B + H)} \leq \sigma_{t\,all}$ $\sigma_t = \frac{\rho_w \times a_o \times H^2 \times (3B - H)}{8 \times t \times (B + H)} \leq \sigma_{t\,all}$

The variables used in Table 3.1 defined as N being the number of perpendicular walls interacting the wall; σ_t is the tensile stress developing at the wall; $\sigma_{t_{all}}$ is the smallest tensile stress capacity (or allowable stress) of the wall material; ω_{out} is the seismic lateral inertial force acting on the unit area of the wall; and a_o is the effective horizontal acceleration acting on the wall. In the first line of Table 3.1, the ceiling's mass is assumed to be shared between the two opposing walls and acting on the wall during an earthquake. On the second line of Table 3.1, the ceiling is assumed to be forming a rigid diaphragm and restrained by the perpendicularly placed walls in their in-plane directions and supporting the top edge of the wall.

When the walls are not restrained at the top level using a rigid diaphragm, the out-of-plane bending failure mechanism defined in the first line of Table 3.1 would always govern. When a rigid diaphragm exists, walls may be more critical in either in-plane or out-of-plane directions. The out-of-plane vulnerability can be assessed by using the second line defined in Table 3.1, while the in-plane strength evaluation requires an analytical approach that involves all structural walls of the house.

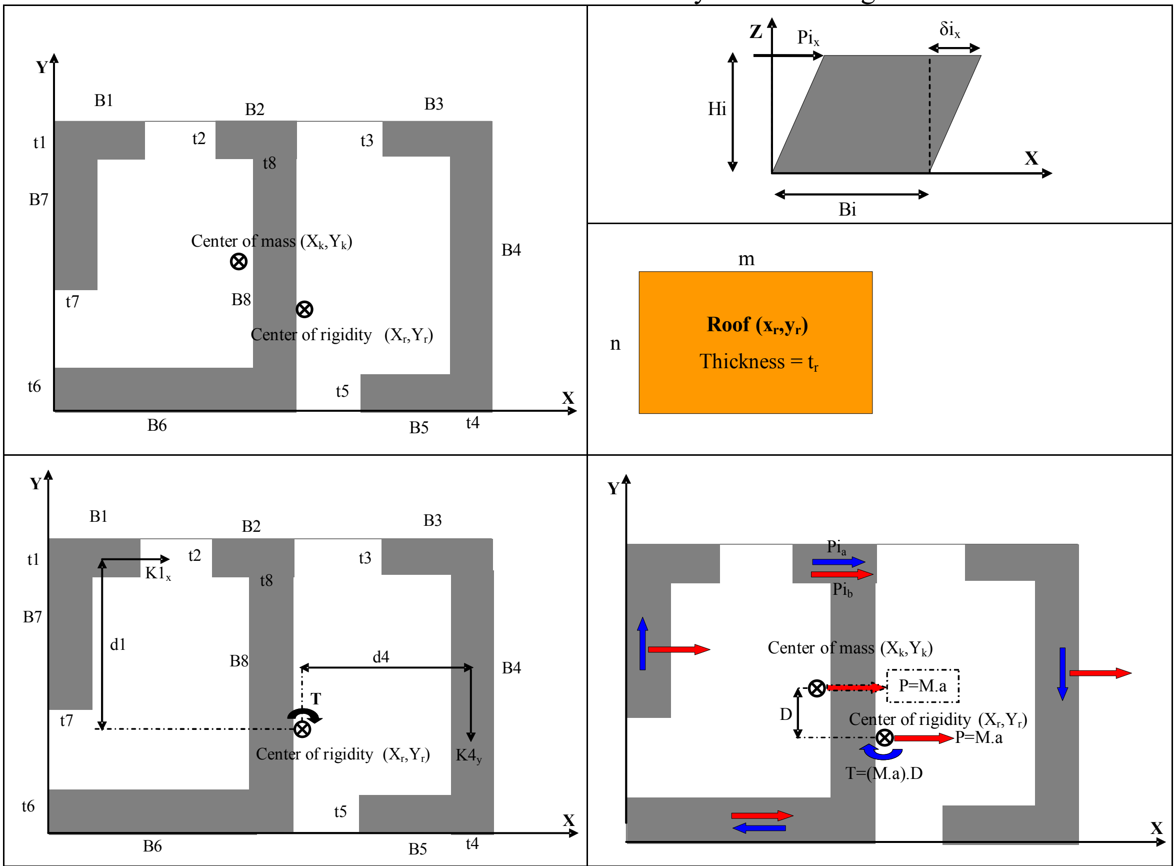
2.2. In-plane failure of the walls

When a rigid diaphragm exists connecting the top of the walls, the inertial forces generated in the horizontal direction are distributed to the walls according to their stiffness. The weaker walls take smaller share of the overall horizontal force while stronger walls take a larger share. The walls that are perpendicular to the direction of loading are assumed to take zero share from the horizontal earthquake forces since stiffness of the walls that are parallel to the forcing direction (in-plane loading) are much stiffer.

Simple, equation based checks are not quite possible for in-plane loading of the walls and basic level of programming is needed to calculate the load demand acting on each wall. It is necessary to compute the rigidity and mass centers of the house to compute eccentricity of inertial forces. The eccentricity would generate torsion on the house creating additional shear forces on the walls. The stiffness values of the walls that are perpendicular to the loading direction (out-of-plane) are assumed to be zero. Furthermore, the in-plane stiffness of each wall is considered on a wall to wall basis, ignoring force transfer between the vertical edges of walls that are perpendicularly connected each other. This assumption was based on the general corner separation commonly observed during earthquakes, which also made the analysis and related programming simpler. The parameters used in the in-plane evaluation are H as the wall height, t as the effective wall thickness at the weakest layer, B as the wall length, A as the wall area (i.e., t×B), δ as the horizontal deflection of wall upper edge in the in-plane direction of the wall, K as the in-plane stiffness, G as the shear modulus, P_i as the in-plane seismic force acting on each wall, ρ_w as the unit mass of the walls, ρ_r as the unit mass of the roof, m as the roof length, n as the roof width, t_r as the roof thickness, a_0 as the spectral earthquake acceleration, S as spectrum coefficient, I as importance factor, R as correction factor, n as the total number of the walls, and F as the total weight on the wall.

The procedure developed to evaluate masonry houses is simple enough to be applied using a tablet PC on the field. The user first sketches a general plan view of the house noting the wall lengths and thicknesses. Window and door openings are considered as void spaces and generate discontinuities for the wall segments. The spreadsheet based program accepts the wall locations as starting and ending coordinates along with the thickness information. The entered coordinates are automatically drawn in a graphical interface for checking the correctness of the entered values. As the developed macro is executed, in-plane stiffness of each wall segment is calculated in the x and y coordinates. If there are any skewed walls, their stiffness are divided in the x and y directions in accordance with the $\cos(\alpha)$ and $\sin(\alpha)$, respectively; α being the skew angle. The mass and rigidity centers are calculated using location information, slab-wall masses, and wall stiffness values. Earthquake demand is calculated using expected peak ground acceleration, soil information, and response spectrum. The structural behavior (reduction) factor 'R' and Importance factor 'I' are both taken as 1.0 for evaluation purposes. The earthquake demand as a lateral force acting at the mass center is distributed to the wall segments assuming a rigid diaphragm as shown in Table 3.2. The vertical force acting on the walls are also taken into consideration and each wall segment is rated using information listed in Table 3.3.

Table 3.2 Data for beams under dynamic loading



In-plane shear force on the wall, $Pi_{(x,y)} = \delta i_{(x,y)} \times Ki_{(x,y)} = \delta i_{(x,y)} \times \dfrac{G \times A_i}{H_i \times 1.2}$

Total mass of the house, $M = \rho_r \times m \times n \times t_r + \rho_w \times \sum_{i=1}^{n} \left(\dfrac{H_i}{2} \times A_i \right)$

Coordinates of center of mass, $X_k, Y_k = \dfrac{\rho_r \times m \times n \times t_r \times (x_r, y_r) + \rho_w \times \sum_{i=1}^{n} \left[\frac{H_i}{2} \times A_i \times (x_i, y_i) \right]}{M}$

Total in-plane stiffness of the walls, $K_{(x,y)} = \dfrac{G}{1.2} \times \sum_{i=1}^{n} \dfrac{A_i}{H_i}$

Coordinates of center of rigidity, $X_r, Y_r = \dfrac{\frac{G}{1.2} \times \sum_{i=1}^{n} \left[\frac{A_i}{H_i} \times (x_i, y_i) \right]}{K_{(x,y)}}$

Total torsion stiffness of the walls, $K_\theta = \sum_{i=1}^{n} \left(Ki_{(x,y)} \times d_i^2 \right)$

Total seismic force and torsion on the house, $P = \dfrac{M \times a_o \times S \times I}{R}$, $T = P \times D$

In-plane force on a wall due to total seismic force, $Pi_{a(x,y)} = \dfrac{P}{K_{(x,y)}} \times Ki_{(x,y)}$

In-plane force on a wall due to total seismic torsion, $Pi_{b(x,y)} = \dfrac{T}{K_\theta} \times d_i \times Ki_{(x,y)}$

Total in-plane force on a wall, $Pi_{(x,y)} = Pi_{a(x,y)} + Pi_{b(x,y)}$

Force acting on each wall develops shear stresses which are transformed into principal tensile stresses since brittle material's failure is governed by tension. The in-plane failure mechanisms are affected by the boundary conditions and aspect ratio of the walls. If a small house with one or two wall segments in the same axis is considered, the top edges of the walls should be accepted as free to rotate, similar to a cantilever beam (Table 3.3 – Column 1). However, if there are multiple wall segments on the same axis connected with a reinforced concrete ceiling, the upper edges of the walls should be considered as restrained against rotation (Table 3.3 – Column 2). The governing failure mechanism can be identified using the last row of Table 3.3. Alternatively, the critical P values can be computed using the second row of Table 3.3 and the equation giving the smallest P value will govern the failure mechanism.

When there are multiple storeys above, the vertical force (F) acting on the wall might alter the failure mechanism. A more detailed formulation was derived in Table 3.4 for different boundary conditions. Equations listed in Table 3.3 can be obtained using equations in Table 3.4 by assigning F as zero.

Table 3.3 Data for beams under dynamic loading

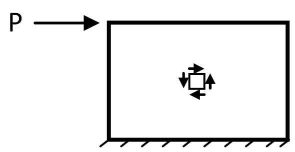
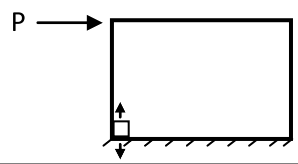
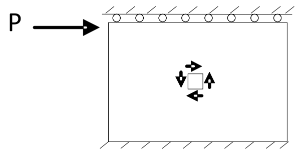
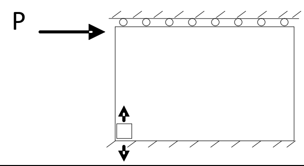
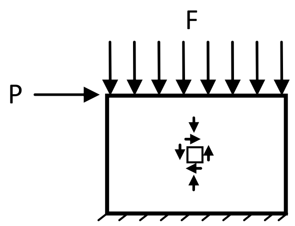
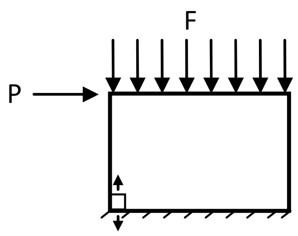
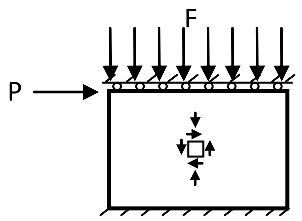
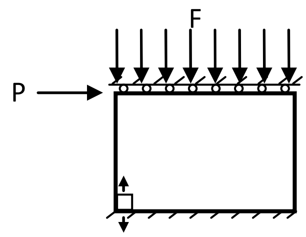
Cantilever idealization for URM wall		Upper edge rotation prevented case for URM wall	
			
$\tau = \sigma_t = \frac{P}{A} \times 1.2 \times 1.5$	$\sigma_t = \frac{P \times H \times \left(\frac{B}{2}\right)}{\left(\frac{B^3 \times t}{12}\right)}$	$\tau = \sigma_t = \frac{P}{A} \times 1.2 \times 1.5$	$\sigma_t = \frac{P \times \left(\frac{H}{2}\right) \times \left(\frac{B}{2}\right)}{\left(\frac{B^3 \times t}{12}\right)}$
For base cracking to govern:		For base cracking to govern:	
$\frac{P \times H \times \left(\frac{B}{2}\right)}{\left(\frac{B^3 \times t}{12}\right)} \geq \frac{P}{B \times t} \times 1.2 \times 1.5; \quad \frac{H}{B} \geq 0.3$		$\frac{P \times \left(\frac{H}{2}\right) \times \left(\frac{B}{2}\right)}{\left(\frac{B^3 \times t}{12}\right)} \geq \frac{P}{B \times t} \times 1.2 \times 1.5; \quad \frac{H}{B} \geq 0.6$	

Table 3.4 Data for beams under dynamic loading

Cantilever idealization for URM wall (Vertically loaded)		Upper edge rotation prevented case for URM wall (Vertically loaded)	
			
$\sigma_t = \left(\sqrt{\left(\frac{F}{2A}\right)^2 + \left(\frac{1.8P}{A}\right)^2} - \frac{F}{2A}\right)$	$\sigma_t = \frac{P \times H \times \left(\frac{B}{2}\right)}{\left(\frac{B^3 \times t}{12}\right)} - \frac{F}{A}$	$\sigma_t = \left(\sqrt{\left(\frac{F}{2A}\right)^2 + \left(\frac{1.8P}{A}\right)^2} - \frac{F}{2A}\right)$	$\sigma_t = \frac{P \times \left(\frac{H}{2}\right) \times \left(\frac{B}{2}\right)}{\left(\frac{B^3 \times t}{12}\right)} - \frac{F}{A}$
For base cracking to govern:		For base cracking to govern:	
$\frac{H}{B} \geq \frac{1}{12}\left[\sqrt{\left(\frac{F}{P}\right)^2 + 3.6^2} + \frac{F}{P}\right]$		$\frac{H}{B} \geq \frac{1}{6}\left[\sqrt{\left(\frac{F}{P}\right)^2 + 3.6^2} + \frac{F}{P}\right]$	

The program computes the seismic demand acting on each wall segment and compares against the minimum of the critical horizontal force (P_{cr}) values given in Eqns. 3.1, 3.2, and 3.3. The equation giving the minimum force (P_{cr}) also determines the governing failure mode. It may be possible that capacities of some narrow and tall walls may be exceeded, which does not necessarily mean that the building will collapse. The program iterates the analysis steps by removing the walls that exceed their loading capacity one by one. The wall with the highest demand/capacity ratio is removed first. Remaining walls share the earthquake force and damaged wall removing process is repeated until either all of the walls get damaged leading to total building collapse or remaining walls successfully carry the earthquake induced forces.

$$P_{cr}^{diagonal} = \frac{A}{1.8} \times \sqrt{\left(\sigma_t + \frac{F}{2A}\right)^2 - \left(\frac{F}{2A}\right)^2} \tag{3.1}$$

$$P_{cr}^{rocking} = \left(\sigma_t + \frac{F}{2A}\right) \times \frac{t \cdot B^2}{6H} \tag{3.2}$$

$$P_{cr}^{sliding} = \left(\tau_{all} \times \frac{A}{1.2}\right) \times \frac{1}{1.5} \tag{3.3}$$

3. EXAMPLE HOUSE

A single storey URM house was selected as the case study for the evaluation part using macro based Excel program. The house is placed in Antakya, Turkey (Figure 1) and has 7.5 m width, 17.5 m length and 2.4 m wall height. To define the wall layout in the program, walls are defined as lines between wall corners and window–door openings.

Figure 1 General view of the evaluated single storey URM house

Basically, in calculation of earthquake demand forces on the house and on the walls, the formulas in Table 3.2 are used. Since the evaluated house is a single storey with a reinforced concrete slab, the conditions in column 2 of Table 3.3 are selected for the calculations. The program has some basic parts including drawing of layout of the walls, placing shear and mass centers graphically, calculating periods in x and y directions, and calculation of the most critical wall's rating factor and defining the governing failure pattern. The user needs to manually remove the most critical wall and rerun the analysis to see if the remaining walls will successfully carry the earthquake force. The wall removal would continue until the load is safely carried or structure will collapse. The necessary parameters to be used in the calculations are elastic modulus of the wall material, horizontal ground peak acceleration, unit weight of the walls and roof, storey height, tension capacity of the mortar, and number of stories. The general appearance of the program is given in Figure 2 along with the drawn data of the example URM house. A 0.3g earthquake acceleration is applied on the house both in X and Y directions separately and the results are obtained as a) number 10 wall has a rating factor of 2 against rocking motion when the earthquake is in X direction, b) number 1 wall has a rating factor of 5 against shear failure when the earthquake is in Y direction. The program gives reasonable results since number 10 wall has the largest aspect ratio as compared with other x direction in-plane walls.

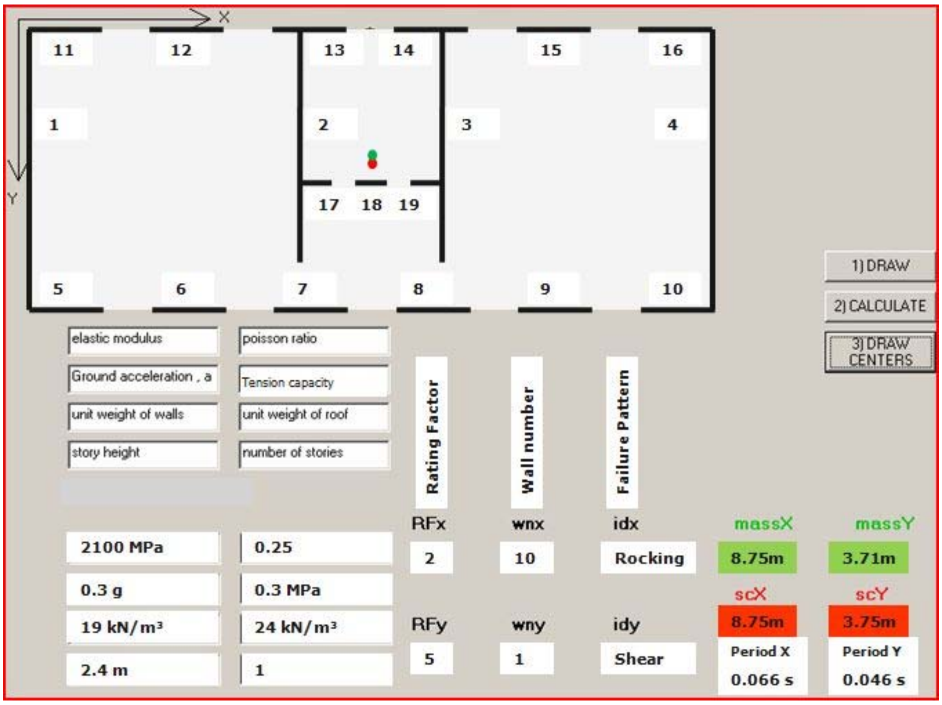


Figure 2 General appearance of the macro based Excel program showing example house data.

4. CONCLUSIONS

General collapse mechanisms of URM house walls were discussed and simplistic seismic evaluation formulas were derived. The "in-plane" and "out-of-plane" capacities of URM walls can be approximately predicted using Table 3.1, Table 3.3, and Eqns. 3.1, 3.2, and 3.3. However, calculation of earthquake demand on the walls for the in-plane shear is more difficult and requires structural analysis. Rules defined in Table 3.2 were used to develop an Excel based program (Figure 2) to calculate earthquake demand on the walls and compare them against capacities to find individual rating factors. An example house (Figure 1) was used to illustrate the use of the program and proposed method. Existing non-engineered URM houses in seismically active and developing countries remain to be a major problem and the proposed seismic evaluation method may be accepted as a handy tool. Although there is a common prejudgment to accept non-engineered URM houses being vulnerable to earthquakes, the example house evaluated in this study has shown that some of those houses may be earthquake resistant. Seismic evaluation and determination of expected collapse mechanisms would enable engineers to prioritize the neediest houses and choose among the available strengthening methods.

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