Guideline on Efficient, and Economic Design of Masonry Units Subjected to Lateral Loads

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***Abstract*—Masonry units (brick, and un-reinforced concrete blocks) constitute a major construction material in Iraq (both northern, southern, and Kurdistan regions), in addition to other materials such as reinforced concrete (RC) and steel. In most applications, the masonry units will be connected to a structural framing system that consists of columns, beams, and roofs. Therefore, the masonry units are mainly subjected to lateral loading, such as wind pressure, and those forces govern the design of the masonry system. At present, structural engineers and designers in Iraq, rely on empirical methods or engineering judgement to design masonry units. Such methods don't have rational basics, and in most times yield an over conservative design. The weak economic situation of Kurdistan region and entire Iraq, urges researchers to seek efficient design methods that reduce labor, equipment, and material costs, while provide a safe usage. This paper presents a guideline on designing masonry members subjected to lateral loading based on the yield line theory and ultimate load strength. First, the members are analyzed by the yield line method which can cover a wide range of boundary conditions and special configurations such as openings. Second, the section capacity of the masonry units is determined according to ultimate strength state, following ACI 530-05 (2005) and NCMA TEK specifications. The ultimate strength method is chosen because it provides a safe and an economic solution for the design of masonry members.**

Keywords-component; masonry; lateral loads; yield line; ultimate capacity

1. INTRODUCTION

The behavior of masonry units (e.g. walls) subjected to lateral loads such as wind pressure is complicated due to the orthotropic nature of the masonry in different directions. When the direction of loading or moments is parallel to bed joints, the bending strength depends on the bond strength between the masonry unit and mortar since it's usually weaker than bending strength of the units. In the other direction (loading or moments are perpendicular to bed joints); the bending strength is affected by multiple factors such as the bond strength and bending resistance of mortar joints, and the strength of masonry units. Therefore, the strength of the masonry unit is different in those two directions.

For analysis and design of masonry walls subjected to lateral loading, elastic analysis methods are applied to masonry. Those methods are considered not easy to handle especially when orthogonal properties are assigned. Only loads at cracking can be obtained at reasonable accuracies, while for failure loads, elastic methods are inappropriate and extremely underestimate the strength [1], and [2]. Another method, which is referred to as "empirical strip method", is also proposed. The method considers horizontal and vertical strips at center of the wall and each strip is assumed to have a unit width. The method seems to correlate reasonably well with experimental results of laterally loaded specimens of masonry walls. However, the method contains the following limitations: (1) it is extremely difficult to deal with different support conditions and special configurations like the presence of openings; and (2) no attempt has been made to ensure deflection compatibility for the two orthogonal strips [1], and [2]. The application of yield line theory for analysis of reinforced concrete slabs has been extended to masonry walls under lateral loads. The merit for the application of yield line theory for analysis of masonry walls is the similarity between RC slabs and masonry walls behavior under lateral loads. Masonry walls tested under lateral loading exhibited crack patterns similar to the conventional yield lines in RC slabs [3], and [4]. The moments coefficients used in the British code of practice for use of masonry [5] are basically derived from yield line theory. Although some researchers argue that the yield line theory, which is intended to be used for ductile material, can't be used for brittle or semi brittle materials like masonry walls [2], other researchers have proved the opposite and argued that the very good correlation between yield line results and experimental data is a great indicator of the applicability of yield line to masonry walls.

Brinker 1984 performed an experimental program consisted of brick masonry walls tested under lateral loading conditions to answer the question of either masonry walls exhibit ductile behavior under lateral loading conditions or no [1]. A combination of different brick and mortar types were considered. The answer was affirmative and all the tested walls exhibited ductile nature in terms of the stress-strain relationship. The stress-strain relationship can be divided into three distinctive phases: first is a linear stage, then a plastic relation with strain-hardening and last, a fracture phase[6] proved the applicability of yield line method for masonry wall applications in a different way by arguing that researchers should look at the energy concept rather than plastic moments. The doubts about yield line theory use in masonry walls initiates from the idea that masonry walls will mostly fail once cracks are observed and will not rotate as similar to plastic hinges in RC slabs. Lovegrove 1988 proposed to use energy concept as a way of conceptualizing masonry ductility [6]. The internal energy required to produce lines called crack lines (not yield lines) is equated to the external work done by applied forces similar to yield line theory; by doing so, the dilemma of masonry wall yieldlines can be resolved.

2. YIELD LINE THEORY

In the yield line theory, the external work (EW) exerted by the lateral pressure loads is equated to the internal work (EW) procured by the sectional moment capacity of masonry units. When equating the two sides, the unknowns can be obtained. For example, if the geometric properties (e.g. block thickness, moment of inertia, etc.) and mechanical properties (e.g. unit's compressive strength) are known, then the equity allows for determination of the maximum lateral pressure that can safely be applied on the member. If the lateral pressure is known, the geometric and mechanical properties will be determined. The yield line theory was introduced by K.W Johanson in late 60s [2]. In this method, a valid failure mechanism is assumed along virtual pattern in the structure called yield lines. Along each yield line, the member is considered to be at its ultimate stage (plastic hinges formed). Each yield line should be straight in topography and should rotate along a specified axis of rotation; the axes of rotation can be supports. The yield line must pass through the juncture of axes of rotation. Furthermore, a yield line is assumed to form parallel to fixed support line. Since several yield line patterns can form in the structure, each one of those patterns should be examined and the pattern that provides the safest outcomes (minimum lateral load, or maximum geometric and mechanical entities) is selected. Figure 1 shows a sketch of possible yield lines formed in masonry sections, having different boundary conditions (B.C) and some special features such as openings.

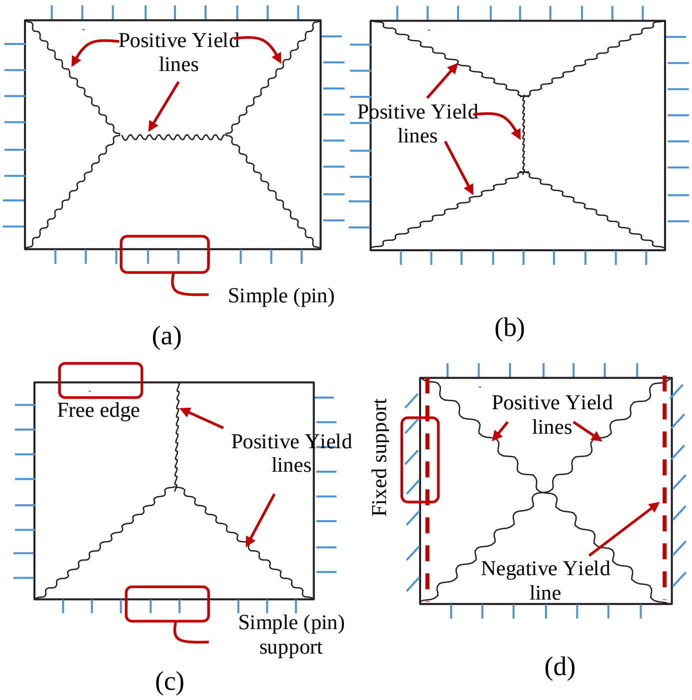
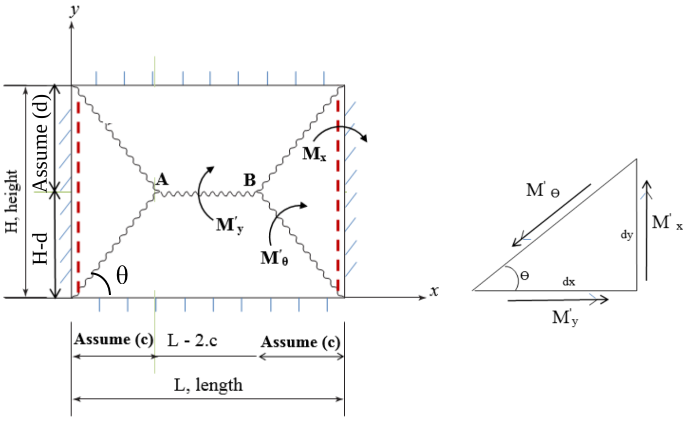


Figure 1 Yield line patterns in masonry walls; (a), and (b) rectangular with simple-support B.C; (c) rectangular with one free edge, (d) square with two fixed B.C

3. APPLICATION OF YIELD LINE THEORY ON MASONRY WALLS

To illustrate the procedure of determining the ultimate capacity of masonry units using the yield line theory, a typical case study is given. The study consists of a masonry wall, that is a part of a building, with rectangular dimensions, simply-supported conditions on top and bottom edges, and fixed at right and left edges. The wall is made of concrete blocks in running bond with face shell bedding. There is no grouting, and there is negligible reinforcement. There are no doors or windows, and there is no vertical load on the top of the wall. The wall given in figure. 2 will be analyzed to determine the wind pressure, *w* (kN/m^2), which will cause failure.



(a) (b)

Figure 2 (a) assumed yield line pattern, (b) transformation of the plastic moment along inclined yield line into two moment components along *x*, and *y* axes.

A. Solution Steps

The assumed plastic-collapse mechanism, shown in figure 2, contains negative yield lines along the right and left rigid supported edges and positive yield lines running diagonally out of each corner where the axes of rotation for adjacent wall segments intersect. No yield lines occur along top and bottom supported edges since those supports are pinned. The locations of point A and the symmetrical point B are defined by the location of line segment length c. Along y-axis, the pattern is assumed to be located at a distance (d) from the top simple support. The symmetry is not induced along y-axis due to the effects of the wall weight on the strength and ultimately on the location of yield lines. An iterative process is required to determine values of c, and d that result in the minimum value for lateral load (*w*).

It's convenient to separate M'_Θ, which acts on an inclined yield lines into two components, M'_x and M'_y, acting on the master axes, (x, y). Considering the differential element in figure 2 (b), the following equation can be drawn:

$$M'_\theta * \frac{dx}{\cos\theta} = M'x * \sin\theta * \frac{\sin\theta}{\cos\theta} * dx + M'y * \cos\theta * dx \quad (1)$$

Simplifying (1) gives:

$$M'_\theta = M'x * \sin^2\theta + M'y * \cos^2\theta \quad (2)$$

B. External Work (EW)

Assuming that the wall in figure 2 will deflect a downward virtual displacement of (δ), figure 3, upon the action of maximum lateral load (*w*) causing the wall to reach near collapse stage, the eternal work can be determined by dividing the wall area into triangular and rectangular segments, figure 3. The external work is as such;

$$EW = w.\,\delta.\left[\frac{a.b}{2} - .\frac{1}{3}\,b.\,c\right] \qquad (3)$$

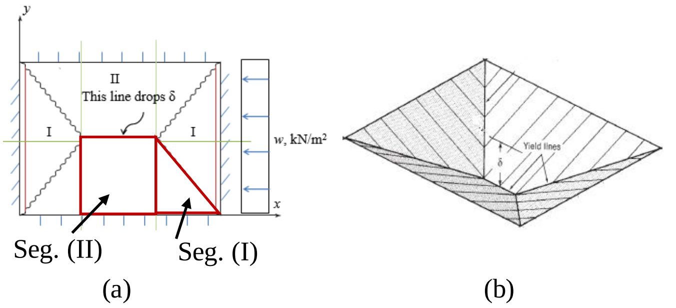


Figure 3 (a) wall divided into triangular and rectangular segments, (b) three-dimensional sketch of displaced wall.

C. Internal Work (IW)

The internal work done by the plastic moments acting on each segment equals to the multiplication of that plastic moment and the projected yield line length on either x or y axes and the rotation angle of the segment. Then, the total internal energy will be the sum of all applicable internal energies.

$$IW = \left[2.\,(M_x + M'_x).\,b.\frac{\delta}{c} + M'_y.\,a.\frac{\delta}{d} + M'_y.\,a.\frac{\delta}{b-d}\right] \qquad (4)$$

Upon equating the external work (eq. 3) with the internal work (eq. 4), the maximum lateral load, *w*, can be deduced.

4. Ultimate Moment Capacities

The moments, M'_x and M'_y, which are needed in calculating the maximum lateral load (*w*), will be calculated based on ACI 530-05 [7] specifications and the national concrete masonry association (NCMA TEK) [8] guides. The strength design method, described in [7], is used in evaluating the section moment capacities. Then, applied moments, M'_x and M'_y, are equated to the appropriate section moment capacity. Strength design method is analogues to the ultimate strength method used in reinforced concrete design. For unreinforced masonry, the following design assumptions are used in calculating the design moments [7]:

1- Plane sections before bending remain plane after bending. Therefore, strain in the masonry, is directly proportional to the distance from the neutral axis.

2- Unreinforced masonry members shall be designed to remain uncracked. Therefore, flexural stresses (tensile and compressive) in the masonry are assumed to be directly proportional to strains.

3- The nominal strength of masonry cross-sections for combined flexure and axial load is based on applicable conditions of equilibrium.

4- The maximum masonry compressive stress is ($0.80xf'_m$), where f'_m is the specified compressive strength of masonry unit, for both reinforced and unreinforced masonry.

5- The maximum masonry tensile stress equals to the modulus of rupture given in [7].

6- The value of the strength reduction factor for unreinforced masonry elements subjected to flexure or axial loads is $\varphi = 0.60$.

For masonry elements subjected to a factored bending moment, Mu, and a compressive axial force, Pu (including only permanent loads such as dead load), the resulting flexural bending stress is determined by the following equation, [8]:

$$F_u = \frac{M_u \times t}{2 \times I_n} \pm \frac{P_u}{A_n} \qquad (5)$$

If the resulting value of *Fu* is positive, then the masonry element is controlled by tension and the modulus of rupture determined from ACI 530, reduced by the appropriate strength reduction factor ($\varphi = 0.60$), must be satisfied. Conversely, if *Fu* as given by equation 11 is negative, the masonry element is in compression and the design compressive stress of 0.80f'm applies.

A. Calculations of M_x and M'_x

For the wall specified in this study and when the bending is in *x*-direction (perpendicular to bed joint), pertaining to M_x or M'_x, as shown in figure 4, there are no acting axial loads; therefore, eq. 11 will reduce to:

$$F_u = \frac{M_u \times t}{2 \times I_n} \qquad (6\text{-a})$$

Further simplification of equation (6-a), gives:

$$M_x = M'_x = M_u = F_u \times S_n \qquad (6\text{-b})$$

Where S_n is the unit's section modulus, and it equals:

$$S_n = \frac{2 \times I_n}{t} \qquad (6\text{-c})$$

M_x and M'_x can be obtained from equation 6-b, by finding F_u, given that section modulus (S_n) is known. To determine F_u, both cases, when compression and tension at extreme fibers, could govern the analysis, in other word:

$$F_u = \text{minimum of} \begin{cases} \varnothing \text{ x } 0.8 \text{ x } f'_m & \text{(for compression)} \\ \varnothing \text{ x } f_r & \text{(for tension)} \end{cases}$$

Where f_r is the unit's tensile modulus of rupture. f_r can be found in ACI-530[8] for masonry units, based on (1) specified compressive strength, f'_m, (2) orientation of moment in accordance with bed joint (i.e. parallel or normal to bed joint), and (3) type of mortar. NCMA TEK [8] provides the geometrical properties, such as a section modulus, S_n.

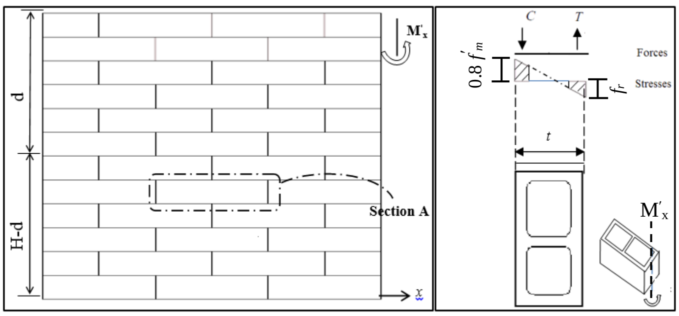


Figure 4 Typical Masonry wall under the action of M_x or M'_x

B. Calculations of M'_y

For the wall specified in this study and when the bending is in M'_y direction (parallel to bed joint) as shown in figure 5, the axial load resulted from the wall self-weight is present and will be combined with bending moment $M'y$ in equation 5; using S_n instead of t and I_n, equation becomes 5:

$$F_u = \frac{M_u}{S_n} \pm \frac{P_u}{A_n} \quad (7)$$

$P_u = 1.4 \times P$ (ASCE 7-05) [9] (8-a)

Where P is the wall's self-weight. Since the positive yield line occurs at a distance (d) from the top support, $M'y$ is acting on that location also, therefore, P, is calculated as:

$P = D \times (d)$ (8-b)

The masonry weight, per unit area, D, is given in [8]. From equation 7, M'_y (same as M_u) can be deduced. Both compression and tension stresses, F_u should be checked, as similar to the procedure followed when determining M_x and M'_x.

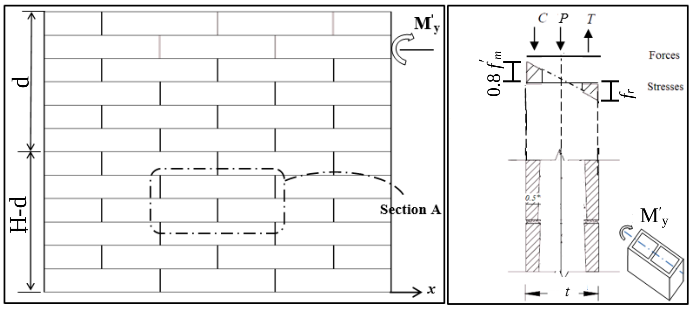


Figure 5 Typical masonry wall under the action of M'_y

C. Procedure

After determining the values of ultimate moment capacities, M_x, M'_x, and $M'y$, equations 3, and 4 are equated to determine the maximum allowable lateral load, w. It should be noticed that an iterative procedure or mathematical solution is needed to solve the equity, since there are three unknowns, w, c, and d. For the iterative procedure, various values for c, and d can be plugged in, allowing for calculation of w. The minimum value of w is then selected. Similarly, any other applicable yield line patterns should also be examined, to estimate the minimum allowable lateral load.

The above procedure can reciprocally be also used to calculate geometric and mechanical properties of the masonry, given that the lateral load value is known. Other boundary conditions or geometrical constraints, such as walls with openings, can easily be solved following the above procedure, and assuming an applicable yield line patterns.

5. Numirical Example

The above wall is 6 m (20 ft.) long and 4.5 m (15 ft.) high. It is made of 250 mm (10 in.) thick concrete blocks in running bond with face shell bedding., with f'_m of 17.2 MPa (2.5 ksi). As mentioned above, the maximum allowable lateral load is determined by equating the external work (equation 3) with the internal work (equation 4). To solve for the lateral load, the iterative (minimization) procedure is followed. Firstly, the value of either c or d is fixed and the other one is varied to see the effects of that variable on w; when the value of the varied unknown that gives minimum w is saved, then the same is done for the other variable. The value of c was first varied while d kept constant, and a value of c=3 m (10ft) gave minimum outcome for w. In the second round of minimization, c was kept as (3 m) while d was varied from 0.3 m (1 ft.) to 4.3 m (14ft). The minimum value of w = 3.3 KPa (66.9 lb/ft^2) occurred when d ranged between 1.5 m (4.9 ft.) to 2.4 m (7.8 ft.). Table 1 shows the results of the second minimization round.

Table 1 Results of minimization of d variable

d (m)	w (KPa)
0.3	5.8
0.6	4.2
0.9	3.6
1.2	3.4
1.5	3.3
1.8	3.3
2.1	3.3
2.4	3.3
2.7	3.4
3	3.6
3.3	3.9
3.7	4.3
4	5.3
4.3	8.4

Conclusions

One of the basic construction units in Iraq is masonry units (concrete blocks, brick units, etc.). Application of masonry in the construction field takes many parts: load bearing members; partitioning of spaces; infill walls, etc. Conventional materials such as concrete and steel have been given great emphasis and their mechanical properties, and behavior are well established. However, In Iraq, not much research has been dedicated to the structural behavior of masonry members. This paper presented a guideline on designing masonry members subjected to lateral loading based on the yield line theory and ultimate load strength. First, the members were analyzed by the yield line method which can cover a wide range of boundary conditions and special configurations such as openings. Second, the section capacity of the masonry units was determined according to ultimate strength state, following ACI 530-05 (2005) and NCMA TEK specifications. The ultimate strength method was selected because it provides a safe and an economic solution for the design of masonry members.

NOTATION

M_x : negative moment resistance per unit length in x-direction.
M'_x : positive moment resistance per unit length in x-direction.
M'_y : positive moment resistance per unit length in y-direction.
M'_Θ: positive moment resistance per unit length in Θ-direction.
Θ : angle between inclined positive yield line and x-axis.
F_u : factored ultimate flexural stress at the extreme fiber of the unit.
M_u : factored ultimate bending moment acting on the section,
A_n : cross-sectional area of masonry unit.
t : net thickness of the block unit.
I_n : moment of inertia of the unit.

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