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CONFINED MASONRY FOR RESILIENT LOW-COST HOUSING IN INDIA: A DESIGN AND ANALYSIS METHOD

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Abstract

Confined masonry (CM) is a viable housing typology that is seismically resilient and economical for application in developing countries. Given its suitability for low-tech environments, multiple authors have published instructions on CM construction that do not require engineering knowledge. As a result, these guidelines impose heavily constrictive design requirements. More precise analysis methods exist for calculating the stress demand on shear walls of a CM building under earthquake loads which may be applied to any design. However, these methods require technical expertise to perform. A procedure for designing CM buildings is presented that employs a combination of seismic analysis techniques to take into account torsional effects and allow for complex designs while requiring low computational effort. Parametric studies are performed on this procedure which show reliable, conservative structural design outputs.

Keywords: confined masonry; low–cost housing; torsional effects; seismic design; irregular buildings

1. Introduction

India and other developing countries are prone to substantial earthquake hazards and housing among the lower economic classes is highly vulnerable to such events. In 2001, for example, building damage was the primary cause of casualties in the Bhuj earthquake that killed over 13,800 people [1, 2]. In poorer sectors materials and workmanship are often low quality and builders are unfamiliar with modern structural techniques [3]. There also exists a lack of motivation to invest in safe homes because most Indians have not been exposed to a devastating earthquake and financial priorities lie in daily life functions. The housing shortage in India is estimated at nearly 60 million homes, and this number continues to grow due to the increasing population and rapid urbanization [4]. This paper focuses on the substantial need for housing solutions in the lower economic classes within India, however it applies to all earthquake prone developing countries.

Approximately 45% of houses in India are made of unreinforced clay brick masonry, and reinforced concrete (RC) frames with masonry infill walls have grown in popularity for the last 35 years [2, 3]. These houses are often built poorly: in the 2001 Bhuj earthquake over 230,000 masonry homes and several hundred RC buildings collapsed [1]. Given the prevalent use of these materials it is clear a better way of building with masonry and RC is needed.

The current study proposes confined masonry (CM) as a solution for seismically resilient housing in India and other developing nations. CM is a structural wall system comprised of load bearing masonry walls with surrounding RC confining elements. CM is attractive for its desirability, cost efficient use of materials, and adequate seismic performance. It is used in many countries, however there are challenges to its widespread use in developing nations such as India.

Advocates publish guidelines to encourage proper use of CM in seismic zones. However, existing guidelines are limited in that they either perform no seismic analysis and heavily constrict the design, or they use analyses which require technical expertise to perform. Herein lies an opportunity for an architectural design guideline for confined masonry which employs seismic analyses while being accessible to architects and builders without an engineering background. This paper outlines a design procedure for CM homes that is intended to empower architects with fair design freedom while guiding them to a structurally resilient solution.

Two existing methods for the design and analysis of CM buildings are combined with a few simplifying adjustments to create the proposed method.

2. Confined Masonry

2.1 Earthquake Performance

Confined masonry is a proposed construction technology for India based on its satisfactory earthquake performance in Latin America and other countries and regions. For example, the 1970 Chimbote, Peru earthquake (M 7.9) killed approximately 70,000 people at a time when adobe construction was predominant for homes. Since then confined masonry has been the most common, and in 2007 the Pisco, Peru earthquake (M 8.0), killed fewer than 600 people [5]. The difference between these two events was due to the shift in construction practice from adobe towards confined masonry after the 1970 earthquake. Some CM structures did suffer severe damage or collapse in the 2007 earthquake due to construction and design deficiencies attributed mainly to informal construction, an issue that is also common in India. However, proper CM construction suffered little to no damage [5, 6, 7, 8]. CM has shown good performance both in past earthquakes and laboratory testing. Open source publications on confined masonry research and its earthquake performance across the globe are available at the Confined Masonry Network's website (confinedmasonry.org).

2.2 Seismic Behavior of CM Walls

CM is a composite wall system that comprises of masonry walls and surrounding RC elements called tie-columns and tie-beams. Masonry walls are the main lateral and vertical load bearing component. The RC elements exist solely to grip the masonry to engage it under lateral loading, provide extra ductility, and prevent out-of-plane failure. The masonry panel develops a diagonal compression strut when resisting lateral loads, initially not relying at all on the RC tie-columns [7]. Once the masonry has cracked, tie-columns provide ductility prior to collapse. Experimental research by Tomazevic and Klemenc [9] illustrates the large increase in ductility of confined versus unconfined masonry which saves lives during an earthquake by giving building occupants extra time to evacuate.

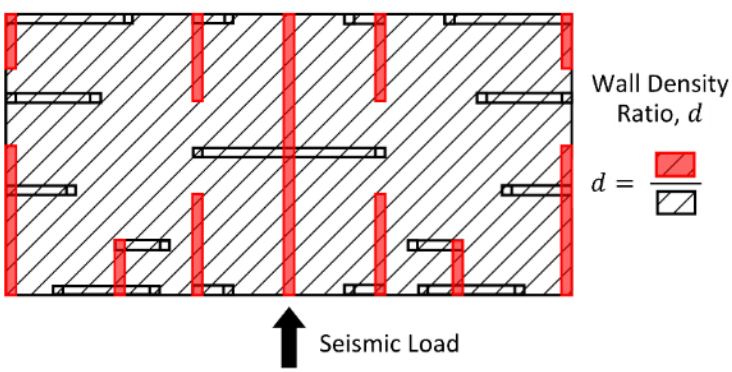


Fig. 1 - Wall density illustrated in the floor plan view above (derived from Meli et al. 2011 [8]).

Table 1. Damage vs Wall Density Relationship from Chile [10]

Level of Damage	Wall Density d/N (%)
light	1.15
moderate	0.85-1.15
severe	0.5-0.85
heavy	< 0.5

The resiliency of a structural wall system such as CM can quantitatively be related to its wall density. Wall density, d, is the ratio in plan of the structural wall area in the direction of applied seismic force to the total plan area of the floor, as shown in Fig. 1. Reports of building performance after the 2007 Pisco, Peru and 1985 Llolleo, Chile earthquakes showed that many of the severely damaged buildings had inadequate wall density [5]. A relationship between the level of damage in a building and the wall density per unit floor based on a survey following the 1985 Chile earthquake is shown in Table 1, adapted from Moroni et al. [10]. Wall density is directly related to shear capacity, and the Simplified Method for Seismic Analysis uses it as the main design criteria for a CM building. Furthermore, CM with adequate wall density is forgiving of minor construction defects [7].

2.3 Why is CM Suitable for India

The RC tie elements in CM buildings are smaller in cross section than infill walls in a RC frame structure because of their lessened role in the structural system [7, 8]. This makes CM attractive because steel and cement are the costliest building materials in India. CM is less expensive than RC frame construction but holds the same appearance, which has aspirational qualities [2, 3, 6]. The seismic performance of CM has been proven in past earthquakes and verified by laboratory experiments. However, there are challenges to its implementation. Engineers in India are reluctant to approve of such small RC elements without design codes. CM construction is also unfamiliar and less mechanized than RC frame construction, and premature failures have been reported due to inadequate design and construction [4].

The proposed method is intended as a preliminary design procedure for engineers that is backed by analysis [17]. It combines the methods of Guzmán and Escobar [11], Tena-Colunga and Cano-Licona [12], and Brzev et al. [13] to create an integrated analysis and design tool that is useful for architects without means to perform a complex analysis themselves. This research aims to bridge the gap between complex analyses and low-tech guidelines that restrict the architectural design.

2.4 Simplified Method for Seismic Analysis

The Simplified Method for Seismic Analysis (SMSA) has been used for design of regular CM buildings since the 1970s and was incorporated in the Mexican masonry code [14]. The SMSA determines the required wall density for a building. It assumes rigid floor diaphragms and ignores torsional effects, so it is applicable only to buildings with regular plan shapes. It also assumes that shear behavior governs for each wall, that is, flexural effects are disregarded. Due to its simplicity and modest computational demand the SMSA is suitable for seismic design of low-rise regular buildings only, such as single-family housing. An advantage of the SMSA over alternative analysis methods is that it is an integrated analysis and design approach. For that reason it has been proposed to expand upon the SMSA for application to buildings with horizontal (plan) irregularities.

2.5 Seismic Analysis of Irregular Masonry Buildings

Walls in buildings with irregular plan shapes or unsymmetrical wall layout experience an increase in seismic demand (internal forces and deformations) due to torsional effects caused by eccentricity of center of mass relative to the center of rigidity. To calculate the increase in wall forces due to torsion is usually complex and requires advanced technical skills and computational tools. A procedure for seismic analysis of irregular buildings developed by Escobar et al. [15] and presented by Guzman and Escobar [11] was considered in this study because it outputs a simple factor for each wall which captures the increase in the shear demand due to torsion. This method alone performs analysis but not design. It is therefore proposed to use this method in conjunction with the SMSA, which will provide the basic structural design requirements. Combined these two methods can be used to facilitate the design and analysis of buildings with a wide range of architectural forms.

3. Seismic Design Procedure

3.1 Introduction

The proposed method can be used to check whether the wall layout and dimensions (length, thickness) are adequate for a given CM building with either a regular or irregular plan shape. First, the SMSA is used to determine a preliminary value for the required wall density. This assumes a square plan with the given footprint area, masonry strength, number of stories, and seismic zone.

For buildings with irregular plan shapes the procedure then involves a torsional analysis given the actual building geometry, assuming only perimeter walls. The method by Escobar et al. [15] is used to determine a torsional amplification factor (TAF) for each wall. The maximum TAF value in each direction is used to determine the design wall density for the direction of the applied seismic force. For this method to apply, the following assumptions must be followed:

- The building is not taller than three stories
- The building plan (width/length) aspect ratio is greater than or equal to 1:3 ($W\!:L \geq 1\!:3$)

- Structural walls are continuous throughout the building height
- There are at least 2 lines of structural walls in each direction
- Floors and roofs act as rigid diaphragms (there is uniform inter-story displacement).

3.2 SMSA Design Procedure

Consider the CM building shown in Fig. 2. The SMSA gives the required amount of structural walls, expressed in terms of the wall density ratio, d (%), in the specified direction of the building plan for given seismic hazard and soil conditions.

$$d = \sum_{\mathrm{i}=1}^{\mathrm{N}} \mathrm{A_i} \Big/ \mathrm{A} \tag{1}$$

where A_i is the cross sectional area in plan of wall i, A is the footprint area of the building, and N is the number of structural walls in the direction of analysis.

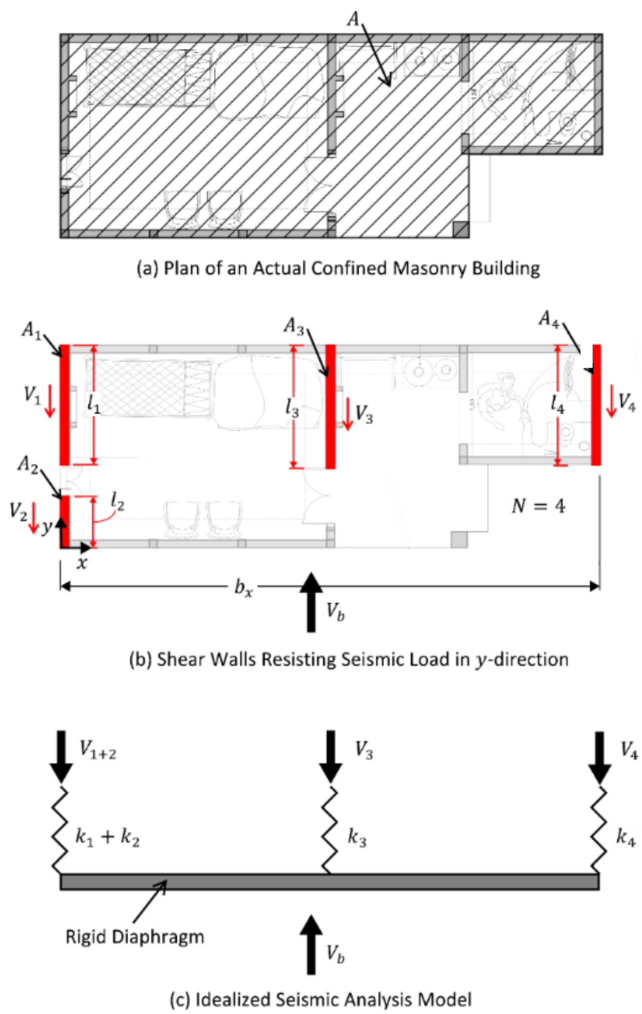
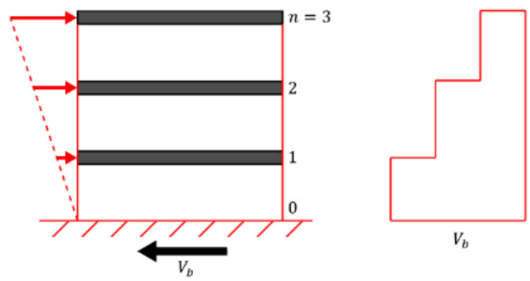


Fig. 2 - Visualization of the SMSA concept. Walls in the direction of the seismic force resist the load in proportion with their relative stiffness to one another.

This is accomplished by comparing the seismic shear demand, V_b, acting at a specific floor level, and the corresponding shear capacity of the story (V_R), as shown in Equation (2).

$$LF \times V_b \leq V_R \tag{2}$$

The analysis is usually performed at the base level where the demand is equal to the seismic base shear force (V_b). The Load and Resistance Factor Design (LRFD) method will be followed in this study, therefore a load factor (LF) is applied to V_b, and a material resistance factor (ϕ) is applied to masonry shear capacity in the V_R equation.



(a) (b)

Fig. 3 - Seismic force distribution along the building height (a)
and the total shear force resisted by each story (b).

The SMSA, as described by Brzev et al. [13], is used to determine a preliminary value for the required wall density in each direction by assuming a regular plan shape and wall layout. The seismic base shear force (V_b) can be expressed as a product of the seismic coefficient (A_h) and the seismic weight (W):

$$V_b = A_h \times W \tag{3}$$

where A_h depends on the seismic hazard, the type of soil, the building importance, fundamental period, etc. The seismic weight (W) can be expressed as a product of the average weight per unit floor area w, the actual floor area A, and the number of stories n, as follows:

$$W = n \times (w \times A) \tag{4}$$

In a building with rigid diaphragms the shear force V_i resisted by wall i at a specific floor level is proportional to its stiffness k_i, see Fig. 2 (c). Since the SMSA assumes that the wall behavior is shear-dominant, the stiffness k is proportional to the wall area A_i based on the fundamental principles of mechanics of solids, that is,

$$k_i = \frac{G \times F_i \times A_i}{H_i} \tag{5}$$

where $G = 0.4E_m$, the shape factor $F = 1.2$ for rectangular sections, and $H =$ wall height.

The shear capacity of a regular building at a particular floor level (V_R) (see Equation (2)) can be determined based on the sum of shear resistances for individual walls at that level. It is assumed that shear resistance of a wall is equal to the product of masonry shear resistance (v_m) and the wall cross-sectional area A_i ; this can be expressed in terms of the wall density d, as follows:

$$V_R = \phi \times (v_m \sum_{i=1}^{N} A_i) = \phi \times v_m \times d \times A \tag{6}$$

The SMSA assumes that each wall has equal shear strength v_m. In this study masonry shear strength, v_m, is determined as function of the compressive strength, f'_m, without considering other factors such as the effects of axial precompression or the shear span ratio (this is a conservative assumption):

$$v_m = 0.18 \times \sqrt{f'_m} \quad (7)$$

The required wall density index, d, can be determined as follows:

$$d = \frac{LF \times A_h \times w \times n}{\phi \times v_m} \quad (8)$$

For regular buildings the wall density determined from Equation (8) is sufficient design output. However, for buildings with more complex plan shapes, torsional effects must be taken into account.

3.3 Simplified Design Method for Irregular Buildings

3.3.1 Introduction – Original Method

The method proposed by Escobar et al. [15] is used to account for torsional effects in buildings with irregular plan shapes. Simplifying techniques are applied to reduce the calculation effort and make the method applicable to a wider range of designs. This method uses a Torsional Amplification Factor (TAF) to account for an increase in the shear demand on walls due to torsional effects. Torsion is induced by eccentricity of stiffness relative to the mass which is associated either with plan shape irregularity, a non-symmetric wall layout, or both. This design method can be used to find a critical TAF for each orthogonal axis of the building plan and subsequently estimate the required wall density for that direction. The underlying concepts are explained in the following section.

3.3.2 The Proposed Design Procedure

Take the building with an irregular wall layout of masonry shear walls shown Fig. 4 (a). In an irregular building with torsional effects the total shear force in each wall, V_{tot_i}, is equal to the sum of the direct shear force, V_{d_i} (without considering torsional effects), and torsional shear force, V_{t_i}:

$$V_{tot_i} = V_{d_i} + V_{t_i} \quad (9)$$

It is assumed that the building has rigid diaphragms, thus a direct seismic force, V_{d_i}, in wall i is proportional to the stiffness of wall i relative to the sum of stiffnesses of all walls aligned in that direction. The story force is taken equal to V_b since the analysis is performed at the base of the building where the seismic force is greatest (see Fig. 3), that is,

$$V_{d_i} = (\frac{k_i}{\sum k_i}) \times V_b \quad (10)$$

Note that V_b is design base shear determined from the SMSA and k_i is the shear stiffness of wall i, see Equation (5). When torsional effects are ignored, the inter-story displacement, Δ, due to force V_b at the base level of the building can be determined from the seismic shear force and the total story stiffness (equal to the sum of the individual wall stiffnesses), as follows:

$$\Delta = \frac{V_b}{\sum k_i} \quad (11)$$

The torsional component of the shear force, V_t, is induced by the torsional moment T_M, which is equal to the product of the applied seismic force V_b and static eccentricity, e_s, see Fig. 4 (b). Eccentricity e_s occurs when the center of mass (C_M) does not coincide with the center of rigidity (C_R), and is the distance between these two locations perpendicular to the direction of applied seismic force. Fig. 4 (a) shows static eccentricity for direction y, e_{sy}, in the building.

Codes in most countries consider the design eccentricity, e_d, as the sum of the static eccentricity, e_s, and the accidental eccentricity which is expressed as a fraction of building plan dimension, b, therefore

$$\left.\begin{array}{c} e_d = \alpha e_s + \beta b \\ or \\ e_d = \delta e_s - \beta b \end{array}\right\} \tag{12}$$

Where $\alpha =$ multiplier for static eccentricity usually taken as 1.5 ($\alpha \geq 1.0$) when accidental eccentricity is positive, and $\delta =$ multiplier for static eccentricity when the accidental eccentricity is negative, usually equal to 1.0.

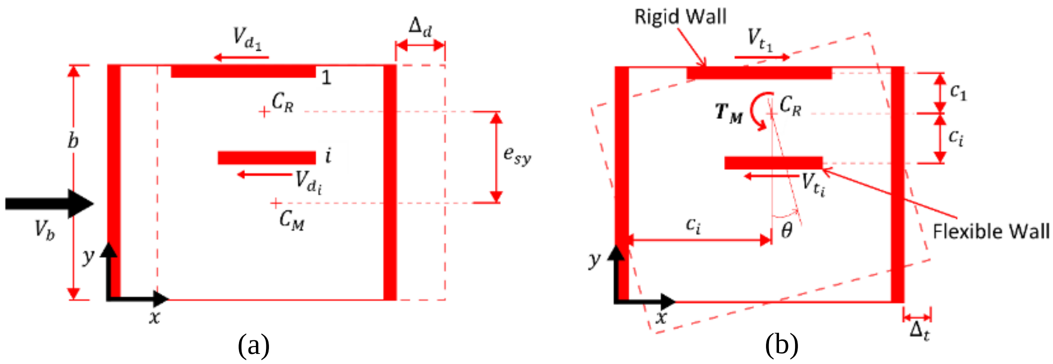


Fig. 4 – Torsional effects for a typical floor plan: (a) wall direct shear forces, V_d, and (b) torsional shear forces, V_t, and the corresponding displacements.

The TAF represents the ratio of the total seismic shear force to the direct shear force, that is:

$$TAF_i = \frac{V_{tot_i}}{V_{d_i}} \tag{13}$$

In this method, a wall is considered as *flexible* (*f*) if it is located on the same side as the center of mass (C_M) with respect to the center of rigidity (C_R), and as *rigid* (*R*) otherwise, see Fig. 5. For elements classified as *flexible*, Equation (14) is used, and for *rigid* elements Equation (15) is used to determine the TAF.

$$TAFf_i = 1 + \frac{\zeta_i}{\rho^2}(\beta + \alpha e) \tag{14}$$

$$\left.\begin{array}{ll} TAFr_i = 1 + \frac{\zeta_i}{\rho^2}(\beta - \delta e) & \delta e < \beta \\ TAFr_i = 1 & \delta e \geq \beta \end{array}\right\} \tag{15}$$

Note that ρ is the normalized radius of gyration, and e is the normalized eccentricity perpendicular to the direction of the applied load:

$$e = {|e_s|}/{b} \tag{16}$$

while e_s is the static eccentricity perpendicular to the direction of the applied load.

The ζ_i factor depends on the distance of wall i relative to C_R, which is labelled c_i and the plan dimension b perpendicular to the direction of applied force, see Fig. 4 (b).

$$\zeta_i = {c_i}/{b} \tag{17}$$

The factor β accounts for accidental eccentricity, which is typically expressed as a fraction of b. In most countries the seismic code prescribes a β value in the range of 0.05 to 0.1.

Given the rigid diaphragm assumption which constitutes that the direct shear force and deflection withstood by each wall is directly proportional to its stiffness, the normalized radius of gyration can be presented as follows:

$$\rho = \frac{1}{b}\sqrt{\frac{k_\theta}{\sum k_i}} \tag{18}$$

Where k_θ is the torsional stiffness:

$$k_\theta = \sum k_i \times c_i \tag{19}$$

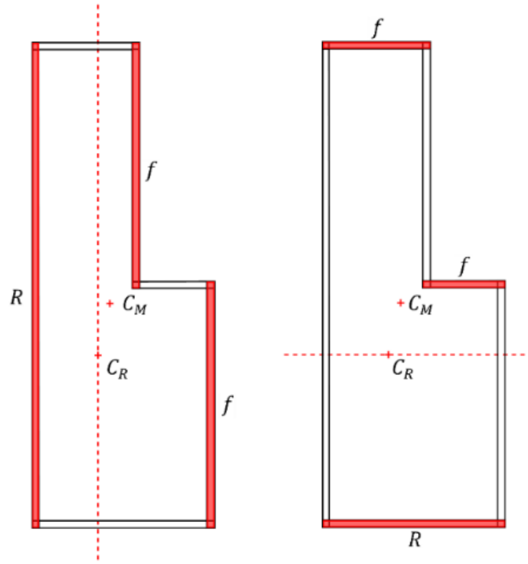
Under circumstances where a shear-dominant behavior is assumed, that is, the stiffness is directly proportional to the wall cross sectional area, the normalized radius of gyration ρ_x for x-direction can be expressed as follows (note that ρ_y can be calculated in a similar manner)

$$\rho_x = \frac{1}{b}\sqrt{\frac{\sum A_i \cdot c_i^2}{\sum A_{xi}}} \tag{20}$$

where A_{xi} and A_{yi} are cross sectional areas of walls in the x- and y-directions, and $\sum A_i$ in Equation (20) includes areas in both directions. When the thickness of all walls at the floor level is constant, this simplifies to:

$$\rho_x = \frac{1}{b}\sqrt{\frac{\sum l_i \cdot c_i^2}{\sum l_{xi}}} \tag{21}$$

$$A_i = l_i \cdot t_i \tag{22}$$



(a) (b)

Fig. 5 – Flexible and rigid walls: (a) flexible walls (*f*) are on the same side of the building plan as C_M, with regard to the reference line through the center of rigidity, C_R, and (b) rigid walls (*R*) otherwise.

3.3.3 Simplifications

The original analysis approach by Escobar et al. [15] has been modified to determine the required wall density for buildings with irregular plan shapes. Once the TAF is found for each wall, the maximum value in each direction is applied to the preliminary wall density in that direction to determine the design wall density d_d:

$$d_d = TAF \times d \tag{23}$$

The following simplifying assumptions are made to reduce the calculation effort and make the design method useful for a wider range of applications: i) the method is limited to buildings with one of the four plan geometries shown in Fig. 6, and ii) the interior layout of the building is unknown, therefore the eccentricity is calculated assuming that all walls are aligned along the perimeter of the building and that the entire perimeter consists of solid structural walls (without openings), see Fig. 6. Since the perimeter walls are the most critical in a building for torsional considerations the latter assumption is considered conservative.

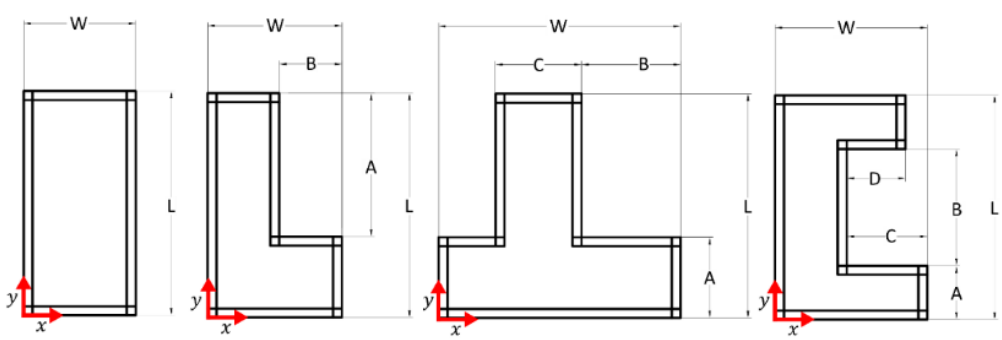


Fig. 6 - The four basic plan geometries that the proposed method is tailored to. It is possible to find the eccentricity and TAF for any combination of the dimensions shown.

The design procedure can be summarized as follows:

1) Using Equation (8) and the SMSA, estimate the preliminary wall density.
2) Use the design dimensions corresponding to those in Fig. 6 to determine the building eccentricities.
3) Calculate the TAF for each perimeter wall. Determine the largest value for each horizontal direction.

4) Apply the critical TAF to the preliminary wall density in each direction, see Equation (23).

3.4 Parametric Study

A parametric study was performed for 45 arbitrary building plan geometries (15 each of "L", "C", and "T" shaped geometries), and the results are presented in Fig. 7. Input parameters were taken from IS 1893 [16]. The output is the TAF which was tested against two parameters, the normalized eccentricity, e/b, and the normalized radius of gyration squared, ρ^2, to investigate their relationships and verify the design method.

The first study of the TAF against the normalized eccentricity, e/b, reveals a strong positive relationship between the two (see Fig. 7a). This chart can be used to predict an increase in the shear stress or force in a building due to torsion given the normalized eccentricity. Furthermore, the even distribution of results shows that the design assumptions (e.g. to consider perimeter walls only for torsional calculations) do not diffuse this relationship and there are no strong outliers; therefore, the design method provides reliable results for a wide range of eccentricities.

The second parametric study investigates the maximum TAF versus the normalized radius of gyration squared, ρ^2, as shown in Fig. 7 (b). The clear inverse quadratic relationship again verifies the function of the design method. Another observation is that as the squared normalized radius of gyration increases past a certain value, the TAF reaches the plateau at 1.1. The value for ρ^2 at which this happens is different for each of the three plan geometries. For "L" shaped building plans, the TAF varies most significantly for ρ^2 range from 0.2 to 0.4. For "T" shaped buildings the plateau occurs after ρ^2 values of approximately 0.5 and 0.3 for the x and y-directions, respectively. For "C" shaped plans this occurs at ρ^2 values of approximately 0.35 and 0.6 for the x and y-directions, respectively. The TAF of 1.1 is therefore a reasonable estimate for values of the squared normalized radius of gyration above those just stated.

3.5 Design Example – Rural Building in Gujarat, India

The proposed method was used to analyze a single story CM rural home in Gujarat, India designed by the Ahmedabad-based architecture firm People in Centre (PiC) [18], see Fig. 8. The home was designed for implementation in the Indira Awaas Yojana (IAY) federal housing project. As with any such program, cost is a key factor for the design and selection of homes, and the CM design was estimated to be 20% less expensive than the next cheapest option designed by PiC.

An in-depth seismic analysis of the design was performed, with a few variables open to alteration to determine the required masonry compressive strength, f_m'. The increase in shear demand for the walls due to torsional effects was determined using a conventional analysis method, and the thickness of the structural walls was the main variable considered. The goal was to recommend a specific design which minimized the required masonry strength while maximizing the cost efficiency.

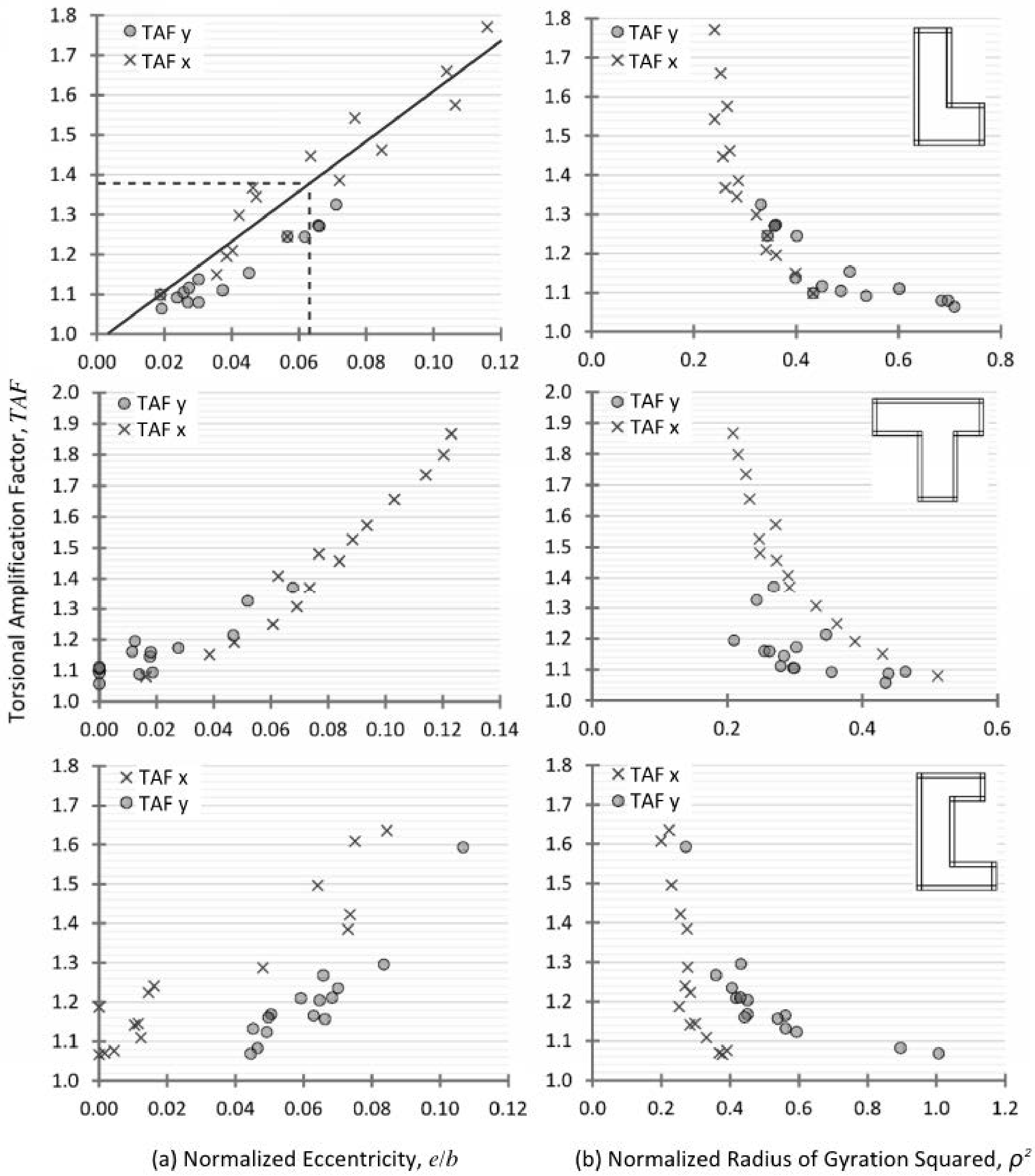


Fig. 7 - Results from parametric studies on 15 buildings with “L”, “T”, and “C” plan shapes.

The proposed method was used for the design and the output was compared to the results of a conventional torsional analysis where the effect of each wall (including the interior walls) was considered. Seismic parameters were obtained from IS 1893 [16] and the chosen site was Bhuj, Gujarat, located in a Seismic Zone V of India. The results of the SMSA, the proposed method, and the conventional analysis are summarized in Table 2. Note the TAF can be determined from a chart in Fig. 7 for “L” shaped plans (shown at top left with a trend line). It can be seen that for the e/b value of 0.063 of this design, the TAF_x according to the trend line is near the 1.34 value found from the calculation; this results in the design wall density value for x-direction d_x of 4.2%.

Normalized eccentricity in the y-direction, $|e_y|/b_y$, is used to predict the torsional effect of x-direction earthquake forces on the building. Note that the eccentricity needs to be determined in the same manner as in conventional torsional calculations.

$$e_y = y_r - y_{cm}$$

Where y_r = y-coordinate of the building's center of rigidity, C_R, as measured from the plan corner of the building demarcated by the axes in Figure 8:

$$y_r = \frac{\sum y_i R_{xi}}{\sum R_{xi}} = \frac{6.1}{2.0} = 3.1m$$

Where y_i = y-coordinate of the wall i centroid; R_{xi} = stiffness in the x-direction of wall i; y_{cm} = y-coordinate of the building's center of mass, C_M, taken by averaging the centers of all walls and floor slabs in the building by their weights. Figure 5 shows a plan view of the center of rigidity and center of mass. Thus,

$$e_y = 3.1m - 3.6m = -0.50m$$

and

$$|e_y|/b_y = |-0.5m|/7.78m = 0.063$$

and b_y = overall y-dimension of the building. Table 2 reveals that the required wall density according to the proposed method is more conservative than that determined from conventional analysis. The result for y-direction walls found using the proposed method is closer to the conventional analysis than for the x-direction because the walls in the y-direction are less affected by torsional effects. This case study shows that the proposed method provides conservative design requirements than more rigorous analysis approaches; this is expected considering the simplifications made.

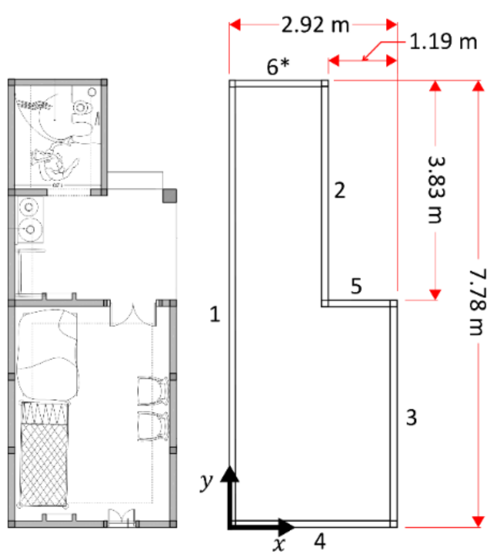


Fig. 8 - Floor plan of a CM rural home (6* *denotes the critical wall* in the x-*direction which was considered in the design*) [18].

Table 2. Wall Density Comparison

	SMSA	Proposed Method	Conventional Analysis	Architectural Design
d_x	2.9	4.2	3.1 (-26%)	4.0 (-5%)
d_y	2.9	3.1	2.9 (-6%)	8.7* (181%)

*The actual y-direction wall density is overdesigned due to the long dimension of the building.

4. Summary

The proposed seismic design procedure for CM buildings uses the SMSA to determine a preliminary required wall density. Subsequently, a method originally developed by Escobar et al. [15] is used with simplifying assumptions to determine the torsional amplification factor (TAF) which is used as a multiplier for the wall density in each orthogonal direction of the building. The assumptions made are: i) the plan shape options are limited, and ii) the eccentricity calculation assumes perimeter walls only. The result is a rapidly repeatable design and analysis method which can be captured in an EXCEL spreadsheet. Studies using the proposed method show reliable, conservative results. This research is intended to empower builders without technical expertise with the ability to design seismically resilient homes.

5. Acknowledgments

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6. References

[1] Jain, Sudhir K. et al. 2002. "Introduction." *Earthquake Spectra* 18 (S1): 1–4. doi:http://dx.doi.org/10.1193/1.2803902.

[2] Murty, C.V.R. et al. 2005. *Earthquake Rebuilding in Gujarat, India*. Earthquake Engineering Research Institute.

[3] Murty, C V R et al. 2006. *At Risk: The Seismic Performance of Reinforced Concrete Frame Buildings with Masonry Infill Walls*. *October*. 2nd ed. Earthquake Engineering Research Institute.

[4] Jain, Sudhir K. 2016. "Earthquake Safety in India: Acheivements, Challenges, and Opportunities." Bull Earthquake Eng **14** (1): 1337-1436.

[5] San Bartolomé, A., and D. Quiun. 2008. "Seismic Behaviour of Masonry Constructions in 2007 Pisco , Peru Earthquake." In *The 14th World Conference on Earthquake Engineering*. Beijing, China.

[6] Blondet, Marcial. 2007. "Behavior of Earthen Buildings During the Pisco Earthquake of August 15, 2007." Earthquake Engineering Research Institute (www.eeri.org/lfe/pdf/peru_pisco_adobe.pdf).

[7] Brzev, Svetlana. 2008. *Earthquake-Resistant Confined Masonry Construction*. National Information Center of Earthquake Engineering (www.nicee.org/confinedmasonry.php).

[8] Meli, Roberto et al. 2011. "Seismic Design Guide for Low-Rise Confined Masonry Buildings." *Confined Masonry Network*. Earthquake Engineering Research Institute (www.confinedmasonry.org/wp-content/uploads/2009/09/ConfinedMasonryDesignGuide82011.pdf).

[9] Tomazevic, Miha, and Iztok Klemenc. 1997. "Seismic Behaviour of Confined Masonry Walls." *Earthquake Engineering & Structural Dynamics* 26: 1059–1071.

[10] Moroni, María Ofelia et al. 2000. "Wall Density and Seismic Performance of Confined Masonry Buildings." *The Masonry Society Journal* 18 (1): 79–86.

[11] Guzmán, Pablo Iván Ángeles, and Escobar, J. Alberto. 2010. "Diseño Por Torsión Sísmica Se Estructuras de Mampostería." Universidad Nacional Autónoma de México.

[12] Tena-Colunga, Arturo, and Jesús Cano-Licona. 2010. "Simplified Method for the Seismic Analysis of Masonry Shear-Wall Buildings." *Journal of Structural Engineering* 136 (5): 511–520. doi:10.1061/(ASCE)ST.1943-541X.0000142.

[13] Brzev, Svetlana et al. 2015. "Simplified Method for Seismic Design of Confined Masonry Buildings." Indian Institute of Technology Gandhinagar (unpublished material).

[14] NTC- M 2004. 2004. *Normas Técnicas Complementarias para Diseño y Construcción de Estructuras de Mampostería (Complementary Technical Norms for the Design and Construction of Masonry Structures)*. Official Gazette of the Federal District of Mexico.

[15] Escobar, J. Alberto et al. 2004. "Evaluación de Criterios de Diseño Por Torsión Sísmica Estática Para Edificos de Varios Pisos." *Revista de Ingeniería Sísmica* 89 (71): 63–89.

[16] IS 1893. 2002. "Criteria for Earthquake Resistant Design of Structures - Part 1: General Provisions and Buildings." New Delhi, India: Bureau of Indian Standards.

[17] Porst, Christopher F. 2015. "Confined Masonry for Sesmically Resilient Low-Cost Housing in India: A Design and Analysis Method." Massachusetts Institute of Technology Department of Civil and Envorinmental Engineering.

[18] People in Centre. 2014. Drawings for the Indira Awaas Yojana (IAY) Federal Housing Scheme. Personal Communication. Ahmedabad, Gujarat, India.