Earthquake-resistant brick masonry housing for developing countries: An easy approach

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ABSTRACT: In developing countries, the general cross-sections of reinforced concrete (RC) vertical and horizontal stiffeners are usually recommended for confined brick masonry houses in earthquake-prone regions. Most of the time, the seismic demand is much less than the provided strength for non-engineered structures. Thus, this makes structure uneconomical and the owner does not follow the design properly. To overcome this problem, there is a need to correlate the seismic demand with the RC stiffeners design. Therefore, in this paper, the optimization of stiffeners is proposed using a diagonal approach in accordance with all governing seismic parameters so that proper design can be followed to meet the required seismic demand with economy. Three variables (cross-section, concrete strength and steel re-bars) are considered for quantization of stiffeners. As a part of validation of the proposed diagonal approach, the unreinforced and reinforced brick masonry structures (UBMS and RBMS, respectively) are analysed for seismic zone 2B and soil profile type SD. The behaviours of UBMS and RBMS are compared for principle critical stress and maximum in-plane top displacement. It is found that RBMS with the proposed cross-sections of RC vertical and horizontal stiffeners is able to cater the required seismic demand. In addition to this, other requirements, limitations and practical issues for earthquake-resistant brick masonry houses are discussed and their convenient solutions are recommended. The purpose of this effort is to ensure both structural safety and economy at the same time.

1 INTRODUCTION

The unreinforced brick masonry structures are seismically venerable to earthquake (Spence 2007). For resisting earthquake loading, the use of reinforced concrete (RC) stiffeners in brick masonry structures is one possible solution. The masonry is oldest and widely used construction method (Rabinovitch and Madah 2011). Brick masonry structural elements are also abundant in historic buildings (Drougkas *et al.* 2016). The losses of property and human lives were due to the collapse of such structural elements during earthquakes. These structures were usually designed for gravity loads only (Naseer *et al.* 2010). These structures were generally constructed from the traditional materials like bricks, wood and stones which are not earthquake-resistant (Arya *et al.* 2012). The majority of unreinforced structures were completely or partially damaged including concrete block masonry, brick masonry and stone masonry during the 2005 earthquake in Pakistan (Shahzada *et al.* 2012). The brick masonry with reinforced concrete stiffeners enhances the strength and stiffness of masonry structures (Thanoon *et al.* 2007). This has been confirmed not only through laboratory testing but also during the real earthquakes. The stiffeners changed failure modes from either shear slip or diagonal tension into a combination of diagonal tension and toe-crushing. The incorporation of reinforcing elements in mortar joints of brick masonry served as a preventive measure for cracking (Dias 2007). Confined masonry walls with horizontal stiffeners performed well compared to non-confined walls when subjected to lateral loading in laboratory (Medeiros *et al.* 2013). Masonry walls with vertical stiffeners in terms of steel ties had significant enhancement in seismic capacity (both strength and ductility) compared to unreinforced walls (Darbhanzi *et al.* 2014). For example, proper construction techniques were being followed in Chile (Dilley *et al.* 2005). Later on, Chile earthquake 2010 with magnitude 8.8 was much more powerful than Haiti's one with magnitude 7.0, but the death toll was considerably lower in Chile (525 deaths) compared to Haiti (316,000 deaths). During Bam earthquake 2003 (M 6.7) in Iran, newly constructed masonry houses with vertical and horizontal stiffeners performed well and saved many lives (Zahrai and Heidarzadeh 2004). The performance of confined brick structures up to six stories was good during Pisco earthquake 2007 (M 7.9) in Peru, because of their inherent large capacity to resist lateral loads (Svetlana 2007). During Java earthquake 2006 (M 6.3) in Indonesia, approximately 154,000 houses were completely collapsed and 260,000 were suffered damage of different nature (EERI 2006). Therefore, it can be claimed from the previous studies that both vertical and horizontal stiffeners are absolute necessary for resisting combination of lateral and gravity loadings in brick masonry structures. To enable an efficient and cost-effective solution, a new concept of constructing structures consisting of coconut-fiber rope reinforcement and interlocking blocks with relative movability at the block interface was also proposed by Ali *et al.* (2012). However, this technique needs to be validated for 3D structure before implementation. Hence, the behaviour of masonry structures during real earthquake, experimental testing and numerical modelling of masonry are discussed in detail in this paper. The current practice is to use generalized cross-section of stiffeners in reinforced brick masonry structure (RBMS) considering broader seismic parameters. Arya *et al.* (2012) considered the design quantization for different items as shown in Table 1. It may be noted that (i) same reinforcement i.e. 2-#10 is recommended for 5 m span of horizontal stiffener for building categories II, III and IV and (ii) the same reinforcement i.e. 1-#16 is recommended for 1, 2 and 3 stories structures in building category III. The difference should exist with a change in building category because 11 combinations are used to define four building categories. But the design output is same for different building categories in case of horizontal stiffeners and for different number of stories in case of vertical stiffeners. This may be the reason for over strength in one case and under strength for other case. That's why, it was concluded in one research that confined masonry houses possessed more energy dissipation capacity than guideline proposed values (Tomazevic and Klemenc 1997). The brick masonry structures in developing countries are shown in Figure 1. The vertical stiffeners at critical locations are missing (refer Figure 1a) in one house and the horizontal stiffeners are missing at the highlighted locations (refer Figure 1b) in other house. The brick masonry structure with appropriate RC vertical and horizontal stiffeners is shown in Figure 1(c).

Table 1: Design quantization for different items by Arya *et al.* (2012)

Item	Sub-item	Building category I	II	III	IV
Mortar mix (cement:sand)	-	1:4 or richer	1:5 or richer	1:6 or richer	1:7 or richer
Reinforcement for horizontal stiffener	5 m span	2 - #13	2 - #10	2 - #10	2 - #10
	6 m span	2 - #16	2 - #13	2 - #10	2 - #10
	7 m span	2 - #16	2 - #16	2 - #13	2 - #10
Reinforcement for vertical stiffener at ground floor	1 storey	1 - #16	1 - #13	1 - #13	NIL
	2 stories	1 - #20	1 - #16	1 - #16	NIL
	3 stories	1 - #20	1 - #16	1 - #16	NIL
	4 stories	Building not allowed		1 - #16	1 - #13

Lourence (1996) reported the modelling of masonry using finite element method with different approaches. There are three types of numerical models i.e. macro, simplified micro and detailed micro models. The micro modelling needs detail information about the mechanical properties and requires strong time demand for analysis (Haach *et al.* 2010). For many engineering application, the use of macro numerical models are reported (Lourence *et al.* 2011 and Medeiros *et al.* 2013). The concept of macro modelling was introduced in 1970. This approach was applied to assess seismic performance of masonry structures (Tomazevic 1978). Medeiros *et al.* (2013) presented the numerical modelling of confined and non-confined masonry walls to validate numerical analysis technique. The numerical macro model was compared with that of experimental work. It was observed that the numerical model was capable of detecting the major features of experimental behavior of tested walls. The material properties used by different researchers for numerical modelling of brick masonry are elastic modulus (E) and poison ratio (υ). The range of E and υ are 1.5-2.5 GPa and 0.13-0.15, respectively, as reported by Medeiros *et al.* (2013) and Tavlopoulou *et al.* (2015). However for this current study, E and υ of 1.5 GPa and 0.15, respectively, are used. All seismic parameters are important and must be taken in to account for the economical and safe design of RC stiffeners for confined brick masonry. This research work considers all seismic factors of equivalent static lateral force procedure. The design of RC stiffeners in brick masonry structures is validated numerically.

2 GUIDELINES, OTHER REQUIREMENTS, LIMITATIONS AND PRACTICAL ISSUES FOR RBMS

Following guidelines by EERI and IAEE (2011) and Arya *et al.* (2012) are helpful for the locations of openings for better resistance of masonry structures against earthquake loadings: (i) *Opening width:* The width of an opening should preferably not be more than 4 ft (1.2 m); (ii) *Opening location:*

Openings to be located away from the inside corner by a clear distance equal to at least 1/4 of the height of openings but not less than 2 ft (600 mm); (iii) *Horizontal gap between two openings:* The horizontal distance (pier width / wall length) between two openings (doors and/or windows) to be not less than half the height of the shorter opening, but not less than 2 ft (600 mm); (iv) *Opening percentage:* The total length of openings not to exceed 50% of the length of the wall between consecutive cross walls in single-storey construction, 42% in two-storey construction and 33% in three storey buildings; (v) *Lintel level:* Keep lintel level same for doors and windows; (vi) *Vertical gap between two openings:* The vertical distance from an opening to an opening directly above it not to be less than 2 ft (600 mm) nor less than 1/2 of the width of the smaller opening. In addition to this, following aspects should also be considered:

The brick size 230 mm x 115 mm x 75 mm is standard size and the actual size is little less (approximately 215 mm x 100 mm x 65 mm, assuming 12.5 mm thick mortar) than the standard size to allow mortar in brick masonry construction. The brick can be broken into smaller pieces but that must be one of the following standard broken sizes: 115 mm x 115 mm x 75 mm, 230 mm x 60 mm x 75 mm, 170 mm x 115 mm x 75 mm and 60 mm x 115 mm x 75 mm and their use must be limited to ensure proper brick bond and integrity of brick masonry. The planning of brick structure must be based on brick standard size. The plan and elevation dimensions of masonry structure must be multiple of 115 mm and 75 mm, respectively. This rule is also applicable for all wall lengths and heights from any horizontal and vertical corners, respectively, within a structure. This means that the width and height dimensions of openings should also be multiple of 115 mm and 75 mm, respectively. This is usually not adopted by designers, forcing masons to use non-standard broken pieces which make the wall weak. English bond is stronger among all brick bonds as it contains a larger proportion of headers (Arya *et al.* 2012). In English bond, vertical joints in the header courses come over each other and the vertical joints in the stretcher course are also in the same line. Therefore, it should be used in confined brick masonry construction. In case, blocks are used instead of bricks. The block size may be substituted with brick size and accordingly rules discussed earlier for bricks should be modified.

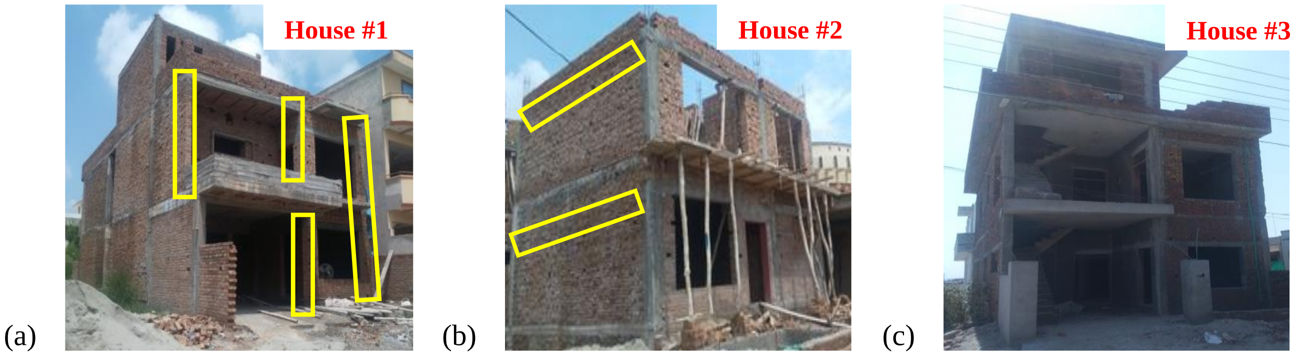


Figure 1: Brick masonry structures in developing countries (a) vertical stiffeners missing, (b) horizontal stiffeners missing, and (c) with appropriate vertical and horizontal stiffeners

3 PROPOSED DESIGN OPTIMIZATION USING A DIAGONAL APPROACH

The summary of the proposed design of reinforced concrete (RC) vertical stiffeners is presented in Figures 2 for different seismic zones and soil profile types with importance factor (I) =1 and Time period (T) of < 0.7 s (i.e. relatively low height buildings e.g. 2-4 storied houses). For design of vertical stiffeners (Figure 2), two concrete compressive strengths (i.e. 15 MPa and 20 MPa), two steel grades (i.e. grade 280 and grade 420 represented as symbols ϕ and #, respectively, with diameter of bars) and two concrete cross-sections (i.e. 115 mm x 115 mm and 230 mm x 230 mm) are opted to meet a particular range of seismic demands. Major variable is diameter and/or number of steel re-bars for any incremental seismic demand. The selected incremental variables for longitudinal re-bars in design output of vertical stiffeners are 1-ϕ6, 1-ϕ10, 1-ϕ13, 1-#10, 1-#13 for concrete cross-section 115 mm x 115 mm and 4-ϕ6, 4-ϕ10, 4-ϕ13 and 4-#10 for concrete cross-section 230 mm x 230 mm. The selected incremental variables for transverse re-bars (i.e. ties) in design output of vertical stiffeners are ϕ6-115 mm/230 mm, ϕ6- 100 mm/200 mm, ϕ6- 90 mm/180 mm, and ϕ10- 115 mm/230 mm for concrete cross-section 230 mm x 230 mm. It may be noted that ties ϕ6- 115 mm/230 mm means ϕ6-115 mm shall be used within both upper and lower quarter heights and ϕ6-230 mm shall be used with in middle half height of the vertical stiffener.

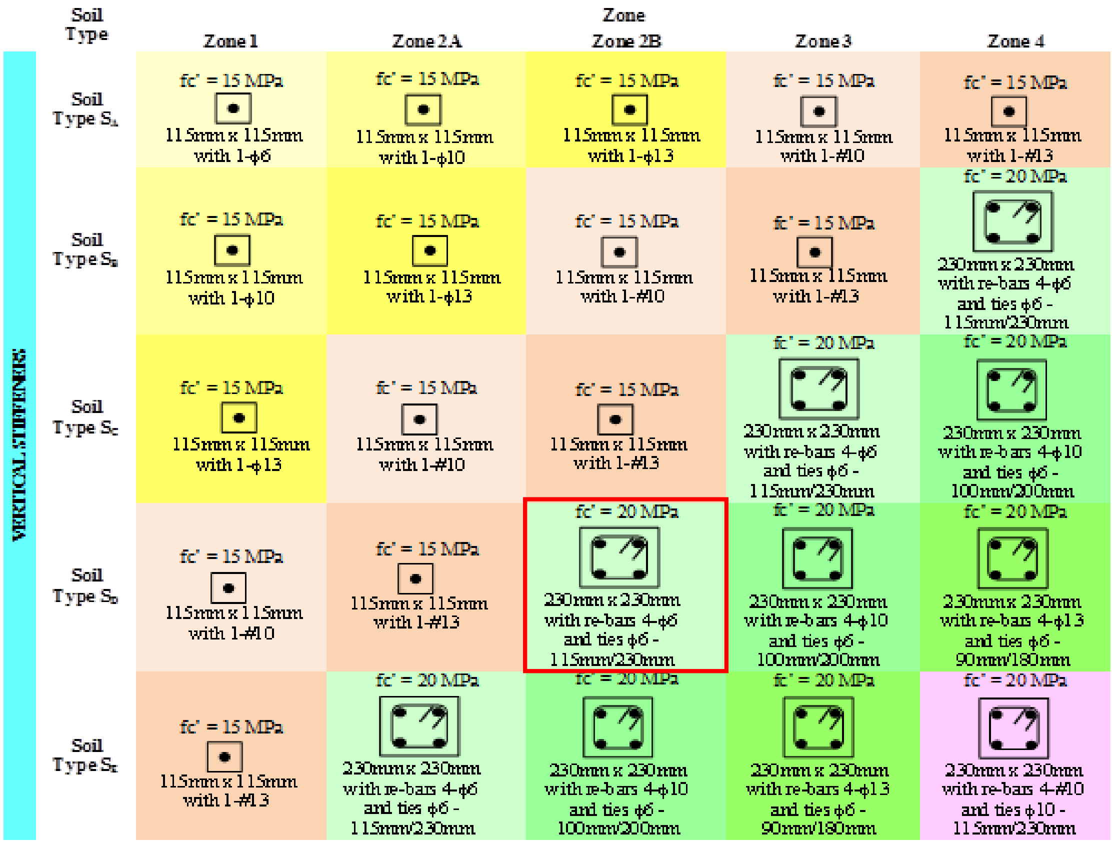


Figure 2: Cross-sectional details of RC vertical stiffeners for different seismic zones and soil profile types with I = 1 and T $\leq$ 0.7s

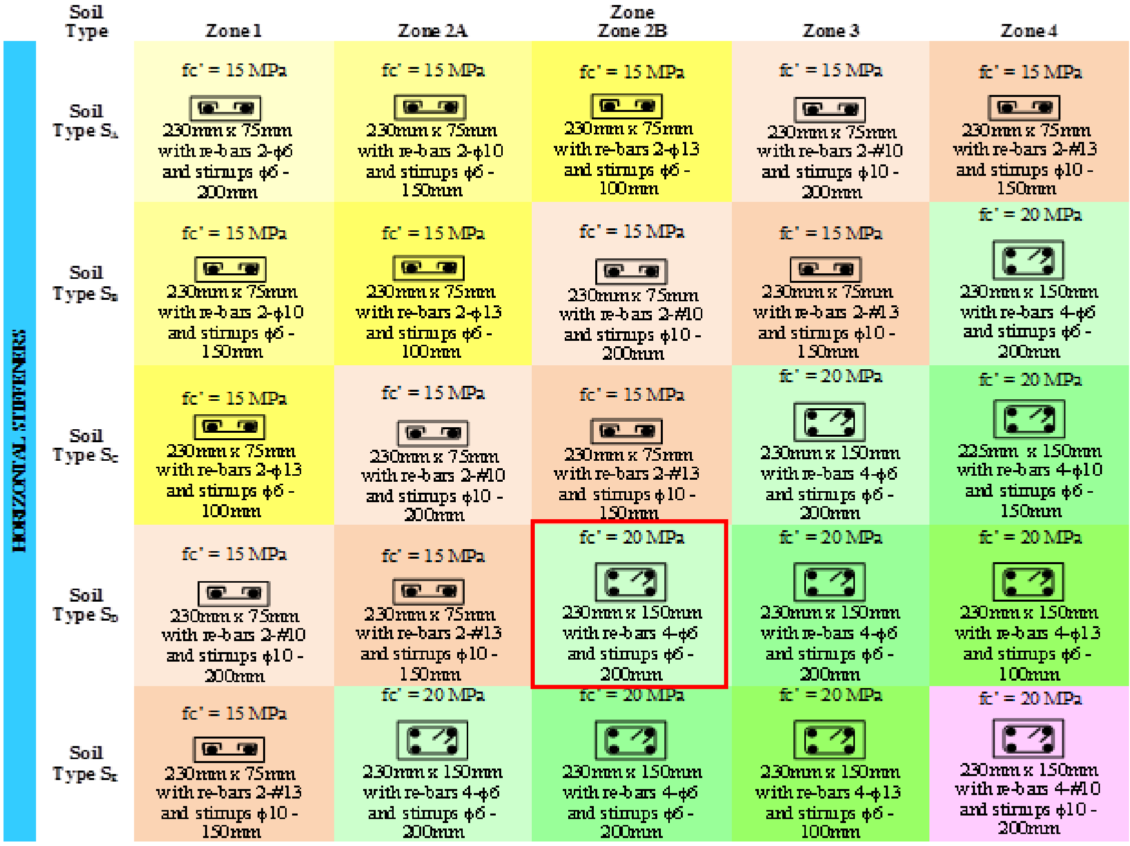


Figure 3: Cross-sectional details of RC horizontal stiffeners for different seismic zones and soil profile types with I = 1 and T $\leq$ 0.7s

The summary of the proposed design of RC horizontal stiffeners is presented in Figures 3 for different seismic zones and soil profile types with I=1 and $T \leq 0.7$ s. For design of horizontal stiffeners (Figure 3), two concrete compressive strengths (i.e. 15 MPa and 20 MPa), two steel grades (i.e. grade 280 and sections (i.e. 230 mm x 75 mm and 230 mm x 150 mm) are opted to meet a particular range of seismic demands. Again, major variable is diameter and/or number of steel re-bars for any incremental seismic demand. The selected incremental variables for longitudinal re-bars in design output of horizontal stiffeners are 2-ϕ6, 2-ϕ10, 2-ϕ13, 2-#10, 2-#13 for concrete cross-section 230 mm x 75 mm and 4-ϕ6, 4-ϕ10, 4-ϕ13, 4-#10 for concrete cross-section 230 mm x 150 mm. The selected incremental variables for transverse re-bars (i.e. stirrups) in design output of horizontal stiffeners are ϕ6-200 mm, ϕ6-150 mm, ϕ6-100 mm, ϕ10-200 mm, ϕ10-150 mm for concrete cross-section 230 mm x 75 mm and ϕ6-200 mm, ϕ6-150 mm, ϕ6-100 mm, ϕ10-200 mm for concrete cross-section 230 mm x 150 mm. In this current study, the proposed vertical and horizontal stiffeners for seismic zone 2B and soil profile type SD is validated numerically as highlighted in Figures 2 and 3, respectively.

4 NUMERICAL MODELLING OF UBMS AND RBMS

A simple house to be made of brick masonry is considered. The first task is to locate the vertical stiffeners. Usually, the vertical stiffeners are provided at corners, at junctions and around openings i.e. doors and windows (Arya *et al.*2012). No previous study has given priority to any of these three locations. If any priority is to be set, then the priority should be in sequence of "at corner", "at junction", "around doors" and finally "around windows". Many studies have provided the guidelines for the location of vertical stiffeners as explained earlier in the introduction section. Figure 4(a) shows the locations of vertical stiffeners according to these guidelines. The total number of stiffeners comes out to be 25. The absolute necessary locations of stiffeners are shown in red colour. The stiffeners at second important locations are shown in cyan colour. The stiffeners with relatively less important locations are shown in green colour. At this stage, the question arises whether these numbers of vertical stiffeners can be reduced or not. Following the above mentioned priority, vertical stiffeners around windows are removed and ground floor plan with reduced number of stiffeners (i.e. with 19 vertical stiffeners) is shown in Figure 4(b). Figure 4(c) shows the ground floor plan with minimum vertical stiffeners (12 numbers). The purpose of the above discussion is to get the optimum number of vertical stiffeners to start with. For this current study, house with 19 vertical stiffeners is considered.

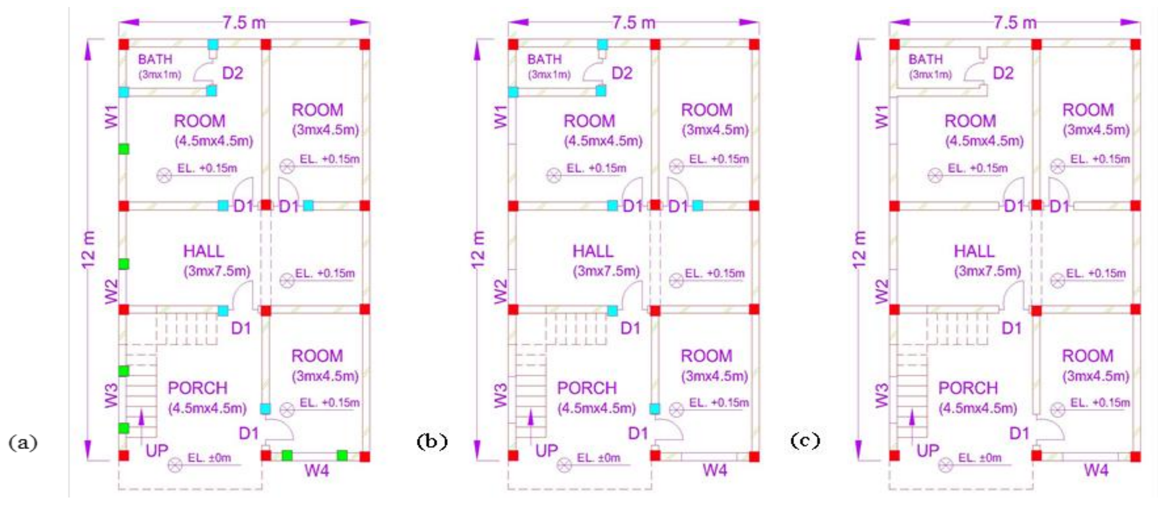
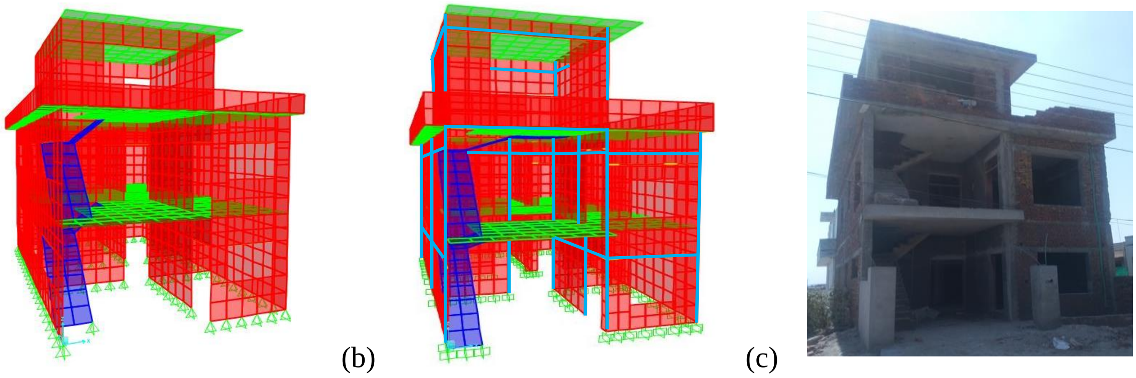


Figure 4: Proposed vertical stiffeners for considered ground floor: (a) at 25 locations, (b) at 19 locations, and (c) at 12 locations

Three dimensional geometrical models of super structure of the considered brick masonry house are developed in SAP2000. The boundary condition at the bottom of the wall at plinth level is taken as hinged support for analysis purpose. This approach is also being used by Shiga *et al.* (1980) and Ranjbaran *et al.* (2012). The macro modelling technique is used. The elastic modulus and poison ratio in current study are 1.5 GPa and 0.15, respectively. Mainly, two models of brick masonry structures are developed i.e. unreinforced brick masonry structure (UBMS) and reinforced brick masonry structure (RBMS) as shown in Figure 5(a) and 5(b), respectively. The model of RBMS is made with RC vertical and horizontal stiffeners as highlighted in Figures 2 and 3, respectively. The original structure under construction is shown in Figure 5(c). The two models are evaluated for combinations of seismic parameter (mainly, soil profile type SD and seismic zone 2B). The analysis are performed with strength reduction factor (R) = 5.5 and I = 1. The time period in both models is < 0.7s..The results of RBMS are compared with that of UBMS.



(a) (b) (c)

Figure 5: 3D view of masonry structures: (a) unreinforced brick masonry structure SAP model, (b) reinforced brick masonry structure SAP model, and (c) original structure under construction

5 RESULTS AND ANALYSIS

Four walls are considered for the explanation of detail analysis (i.e. principal critical stress and maximum in-plane top displacement) of seismic performance of UBMS and RBMS: the longitudinal wall with openings, longitudinal solid wall, transverse wall with opening, and transverse solid wall.

5.1 Principle critical stress (PCS) in UBMS and RBMS

The principle critical stress (PCS) is the maximum stress (tensile, compressive or shear) used for design purpose at a point on a surface of stressed body or structure (Beer 2009). The PCS in longitudinal wall with openings of UBMS and RBMS for seismic zone 2B and soil profile type SD are shown in Figure 6. It is noted that the PCS in longitudinal wall with openings is 1.85 MPa for UBMS and 0.80 MPa for RBMS. Thus, the PCS in longitudinal wall with openings of RBMS is decreased by 57% compared to that of UBMS. The PCS in longitudinal solid wall are 0.84 MPa and 0.32 MPa for UBMS and RBMS, respectively. The PCS in longitudinal solid wall of RBMS is reduced by 62% with respect to that of UBMS. The PCS in transverse wall with openings of UBMS is 0.77 MPa and that of RBMS is 0.25 MPa. In transverse wall with openings of RBMS, there is a decrement in PCS by 68% as compared to that of UBMS. The PCS in transverse solid wall of UBMS is 0.75 MPa. The PCS in transverse solid wall of RBMS is 0.24 MPa. In transverse solid wall of RBMS, there is a decrement in PCS by 68% as compared to that of UBMS. The reason for decrement in PCS of RBMS is the provided vertical and horizontal stiffeners of sizes 230 mm x 230 mm and 230 mm x 150 mm, respectively. The principle critical stress of considered walls for seismic zone 2B and soil profile type SD are shown in Figure 7. Generally, the PCS is reduced up to 57%-68% in considered walls of RBMS compared to that of UBMS.

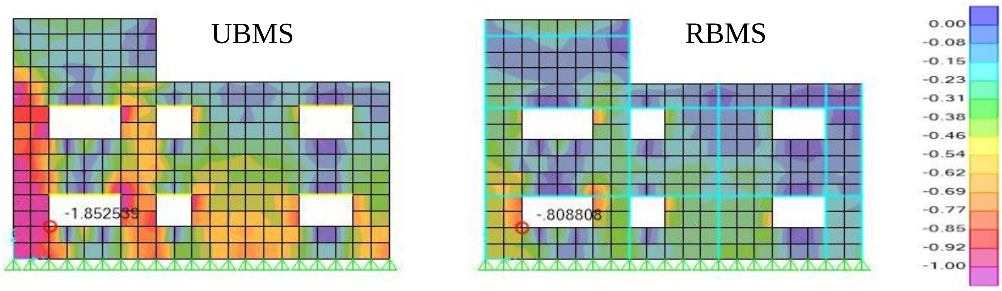


Figure 6: Principle critical stress in longitudinal wall with openings for seismic zone 2B and soil profile type SD

MPa

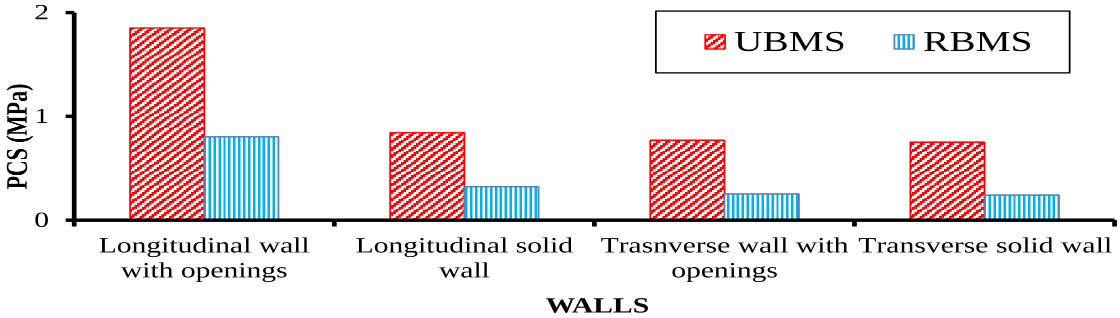


Figure 7: Principle critical stress in considered walls for seismic zone 2B and soil profile type SD

5.2 Maximum in-plane top displacement (Δ) in UBMS and RBMS

The Δ in longitudinal wall with openings of UBMS is 3.34 mm and in RBMS, it is 2.44 mm. In longitudinal wall with openings of RBMS, the Δ is decreased by 27% compared to that of UBMS. The Δs in longitudinal solid wall are 3.19 mm and 2.27 mm of UBMS and RBMS, respectively. The Δ in longitudinal solid wall of RBMS is reduced by 29% with respect to that of UBMS. The Δ in transverse wall with openings of UBMS is 1.55 mm and that of RBMS is 1.10 mm. Thus, the Δ is decreased in transverse wall with openings of RBMS by 29% compared to that of UBMS. The Δ in transverse solid wall of UBMS is 1.14 mm. The Δ in transverse solid wall of RBMS is 0.80 mm. In transverse solid wall of RBMS, there is a decrement in Δ by 30% as compared to that of UBMS. The reason for decrement in Δ of RBMS is the provided vertical and horizontal stiffeners of sizes 230 mm x 230 mm and 230 mm x 150 mm, respectively. The maximum in-plane top displacement of considered walls for seismic zone 2B and soil profile type SD are shown in Figure 8. Generally, the Δ is reduced up to 27%-30% in walls of RBMS compared to that of UBMS.

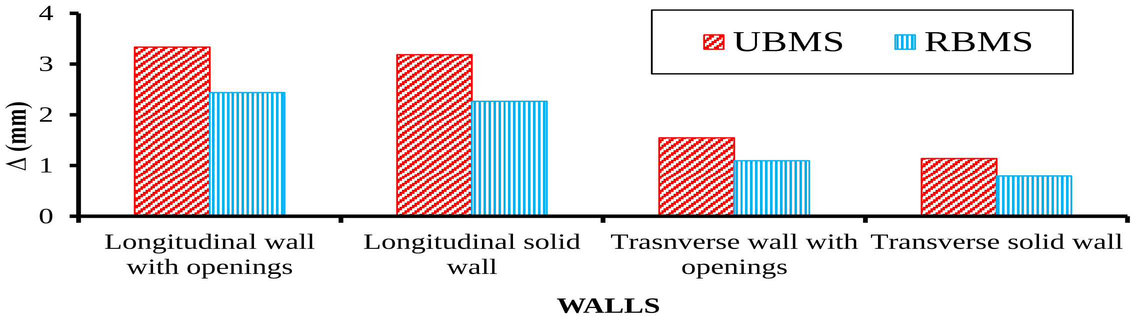


Figure 8: Maximum in-plane top displacement of considered walls for seismic zone 2B and soil profile type SD

5.3 Prediction of crack propagation in UBMS and RBMS

Tomazevic and Klemenc (1997) reported masonry's compression and tensile strengths of 1.27 MPa and 0.12 MPa, respectively, obtained by testing unreinforced masonry walls. Sandoval and Arnau (2016) reported the masonry's average shear strength of 0.76 MPa through experimental characterization and detailed micro-modelling of brick masonry. In this current study, the shear stress is critical and therefore considered as PCS. The limits of crack predication for PCS and Δ are 0.80 MPa and 3 mm, respectively. If the PCS or Δ is beyond these limits, the cracks will likely to be appeared in the structure. The prediction of crack propagation in longitudinal wall with openings (viewed from the inside) for seismic zone 2B and soil profile type SD is shown in Figure 9.

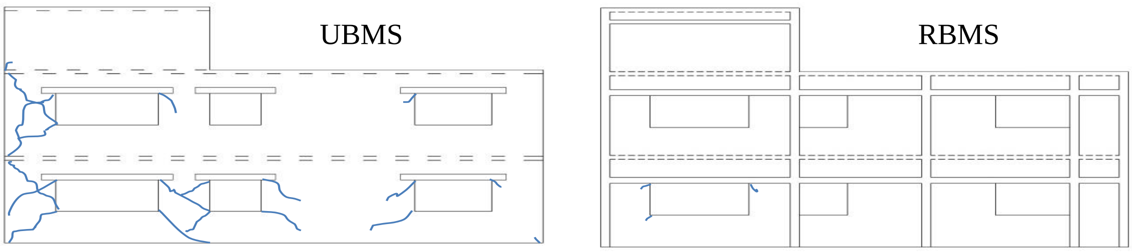


Figure 9: Prediction of crack propagation in longitudinal wall with openings (viewed from the inside) for seismic zone 2B and soil profile type SD

6 CONCLUSION AND RECOMMENDATIONS

The reinforced concrete (RC) vertical and horizontal stiffeners for different seismic parameters (soil profile types, seismic zones, importance factor, and time period) are proposed using a diagonal approach. Three dimensional geometrical models of a brick masonry house as unreinforced brick masonry structures (UBMS) and reinforced brick masonry structures (RBMS) are developed in SAP2000 using macro modelling technique. The principal critical stress (PCS) and maximum in-plane top displacement (Δ) are compared for UBMS and RBMS for seismic zone 2B and soil profile type SD. Following conclusions are made:

1. Seismic performance of RBMS is better than UBMS for seismic zone 2B and soil profile type SD, as expected. Fewer cracks appeared in RBMS compared to UBMS.
2. There is decrement in PCS up to 57%-68% in walls of RBMS compared to that of UBMS.
3. There is reduction in Δ up to 27%-30% in walls of RBMS compared to that of UBMS.

These results indicate that the proposed RC vertical and horizontal stiffeners can be used for making brick masonry structures earthquake-resistant and economical. Thus, the proposed design optimization using a diagonal approach seems workable. Therefore, future recommendations are; the proposed RC vertical and horizontal stiffeners using a diagonal approach for all seismic zones and all soil profile types should be validated numerically. Further verification using dynamic analysis is also necessary.

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