Seismic Performance of Unreinforced and Reinforced Brick Masonry Structures by Numerical Modelling for Design Optimization

By

Mehran Khan
(MCE153011)

MASTER OF SCIENCE IN CIVIL ENGINEERING
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ISLAMABAD, PAKISTAN

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A research thesis submitted to the Department of Civil Engineering,
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CERTIFICATE OF APPROVAL

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THESIS EXAMINING COMMITTEE

S No	Examiner	Name	Organization
(a)	External Examiner	Engr. Dr. Faisal Shabbir	UET, Taxila, Pakistan
(b)	Internal Examiner	Engr. Dr. Ishtiaq Hussan	CUST, Islamabad, Pakistan
(c)	Supervisor	Engr. Dr. Majid Ali	CUST, Islamabad, Pakistan

Engr. Dr. Majid Ali
Thesis Supervisor
January, 2017

Engr. Dr. Muhammad Atiq-Ur-Rehman Tariq
Head
Department of Civil Engineering
CUST, Islamabad, Pakistan
Dated : January, 2017

Engr. Prof. Dr. Imtiaz Ahmad Taj
Dean
Faculty of Engineering
CUST, Islamabad, Pakistan
Dated : January, 2017

Certificate

This is to certify that Mr. Mehran Khan (Reg # MCE153011) has incorporated all observations, suggestions and comments made by the external as well as the internal examiners and thesis supervisor. The title of his thesis is: "Seismic Performance of Unreinforced and Reinforced Brick Masonry Structures by Numerical Modelling for Design Optimization".

Forwarded for necessary action.

Engr. Dr. Majid Ali
(Thesis Supervisor)

DEDICATION

This effort is dedicated to my respected and affectionate parents, who helped me through all difficult times of my life and sacrificed all the comforts of their lives for my bright future. This is also a tribute to my honorable teachers who guided me to face the challenges of life with patience and courage, and who made me what I am today.

Mehran Khan
MCE153011

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LIST OF ABBREVIATIONS

E	Elastic modulus of brick masonry
H.S	Horizontal stiffener
I	Importance factor
M	Magnitude
PCS	Principle critical stress
R	Response modification factor
RBMS	Reinforced brick masonry structure
T	Time period
UBC 97	Uniform Building Code 1997
UBMS	Unreinforced brick masonry structure
V	Base shear
V.S	Vertical stiffener
υ	Poison ratio of brick masonry
Δ	Maximum top displacement
ϕ	Grade 280 (i.e. Grade 40) steel rebar
#	Grade 420 (i.e. Grade 60) steel rebar

ABSTRACT

Most of the residential houses are constructed with unreinforced brick masonry in many earthquake-prone regions. These structures are not safe against seismic loading. In absence of proper guidelines, researchers have recommended the use of reinforced brick masonry considering broader seismic parameters. Most of the time, the seismic demand is much less than the provided strength even with the use of minimum stiffeners cross-section, concrete strength and reinforcement re-bars. Thus, generalized cross-section of stiffeners is proposed. This practice does not consider all seismic parameters and ultimately engineers recommend stiffeners of heavy design to ensure safety. To overcome this problem, there is a need to correlate the seismic demand with the stiffeners design.

The design optimization of reinforced concrete (RC) vertical and horizontal stiffeners in brick masonry structures using a diagonal approach is important. In this research work, the proposed design of RC vertical and horizontal stiffeners is validated numerically in accordance with governing seismic parameters i.e. $I = 1$ and $T \leq 0.7$ second.

The purpose of this effort is to ensure both structural safety and economy at the same time. A total of 50 numerical models of brick masonry structures are developed and analysed in SAP2000 for different seismic parameters. The seismic performance of unreinforced brick masonry structure (UBMS) and reinforced brick masonry structures (RBMS) is studied in terms of principle critical stress (PCS), maximum top displacement (in-plane) and prediction of crack propagation. The behaviour of different RBMS are compared with that of UBMS.

As anticipated, RBMS (with proposed stiffeners) performed better than UBMS for respective seismic loadings. In RBMS, the PCS of both walls (i.e. wall with openings and solid wall) are reduced up to 68% compared to that in UBMS. The maximum top displacement (Δ) of RBMS in wall with opening and solid wall are decreased up to 33% and 37%, respectively, compared to that of UBMS. The length and number of cracks in RBMS are less compared to that of UBMS for all soil profile types and seismic zones. It is concluded that the proposed optimized stiffeners in RBMS meet the required seismic demand for that particular combination of seismic loadings. Based on these results, the proposed diagonal approach for design of vertical and horizontal stiffeners in brick masonry structures is safe and economical.

LIST OF INTENDED PUBLICATIONS

Intended journal article

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CHAPTER 1

INTRODUCTION

1.1 Prologue

In the world, unreinforced masonry buildings are one of the most seismically vulnerable structure types (Spence 2007). The masonry buildings are constructed in many parts of the world where earthquake occurs. Most of the losses of property and human lives were due to the collapse of such structures during earthquakes. These structures were either designed for gravity loads only or due to the construction in the absence of code (Naseer *et al.* 2010). These structures were constructed from the traditional materials like bricks, wood, adobe and stone which are not earthquake-resistant materials (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). A French contractor and structural engineer, Paul Cottancin, proposed stiffeners to strength masonry buildings at the end of 20^{th} century (Edgell 1985). The brick masonry is the oldest and widely used construction method (Kamal *et al.* 2014). These structures are not safe against seismic loading. In absence of proper guidelines, researchers have recommended the use of reinforced brick masonry considering broader seismic parameters (Amjad 2009 and Arya *et al.* 2012). This practice does not consider all seismic parameters and ultimately engineers recommend stiffeners of heavy design to ensure safety. Most of the time, the seismic demand is much less than the provided strength even with the use of minimum stiffeners cross-section, concrete strength and reinforcement re-bars. Low seismic demand is required in regions of mild seismic zone (e.g. zone1) and good soil profile types (e.g. SA). Similarly, it is likely in some cases that the provided strength of stiffeners is not sufficient for high seismic demand (e.g. in region of seismic zone 4 and soil profile type SE). Nowadays, 9 inch x 9 inch RC stiffeners are used in the brick masonry structures which is an engineered practice and sometimes become unsafe or uneconomical. For different seismic parameters, the RC stiffeners cross section and reinforcement ratio should be different. Thus, the concept of design optimization of RC stiffeners for different seismic parameter using a diagonal is important. This approach needs to be validated numerically.

1.2 Research motivation

The Kashmir earthquake (also known as the South Asian earthquake or the Great Pakistan earthquake) of 2005 designates as a major earthquake (Magnitude 7.6) with its epicenter in the Pakistan-administered Kashmir at a depth of 19 Km (EERI 2006). The buildings, hospitals, schools, and rescue services were paralyzed. Approximately 138,000 peoples were injured and over 3.5 million rendered homeless (EERI 2006). According to Government figures, 19,000 children died in the earthquake, most of them in widespread collapses of school buildings (EERI 2006). The earthquake affected more than 500,000 families (EERI 2006). The motive of this research is to provide safe and economical earthquake-resistant housing technique to public.

1.3 Overall and specific research objectives

The overall objective of the research program is to improve construction technique (with safety and economy) by design optimization of reinforced concrete stiffeners in brick masonry structures for different combination of seismic parameters. As stated earlier, the design optimization of concrete stiffener, by using a diagonal approach, is proposed by research group.

In this research work, the comparative evaluation of seismic performance of reinforced brick masonry structures (RBMS) with respect to unreinforced brick masonry structures (UBMS) by numerical approach is studied. Thus, the specific goal of this research thesis is as follow:

> *"To validate, numerically, the design optimization of reinforced concrete vertical and horizontal stiffeners in brick masonry structures with $I = 1$ and $T \leq 0.7$ second".*

1.4 Research methodology

A three dimensional geometrical model of brick masonry structure is developed in SAP2000. The macro modelling technique is used for generating the brick masonry. Mainly, two models of brick masonry house (commonly constructed in the local region i.e. Islamabad, Pakistan) i.e. unreinforced brick masonry structure (UBMS) and reinforced brick masonry structure (RBMS) with different configuration of RC stiffeners are developed. These structures are evaluated for different seismic parameters (soil profile types and seismic zones) with R=5.5, I=1 and $T \leq 0.7$s. The seismic performance of UBMS and RBMS is studied in terms of principle critical stress, maximum top displacement and the predication of crack propagation. The results of different RBMS are compared with that of UBMS. The proposed stiffener cross section and steel reinforcement are validated numerically.

1.5 Thesis layout

The thesis layout comprises of main six chapters. These are:

Chapter 1 consists of introduction. It explains about the background of UBMS and RBMS, research motivation, research objective, methodology, and thesis layout.

Chapter 2 contains the literature review. It consists of background, behavior of UBMS and RBMS, guidelines of RBMS, numerical modelling techniques of brick masonry structure, macro modelling technique and summary of chapter 2.

Chapter 3 explains the concept of design optimization using a diagonal approach. It mainly includes explanation of diagonal approach, cross-sectional details of RC vertical and horizontal stiffeners, and summary.

Chapter 4 consists of numerical modelling of UBMS and RBMS. It mainly contains selection of house and location of stiffeners, macro modelling of selected house as UBMS and RBMS, and summary of chapter 4.

Chapter 5 consists of results and analysis regarding the seismic performance of UBMS and RBMS. It gives details about principle critical stress, maximum top displacement, predication of crack propagation, comparison of principle critical stress and maximum top displacement, validation of diagonal approach, and summary of results.

Chapter 6 consists of conclusion and recommendations.

All references are listed after chapter 6.

There are annexures A, B, C, D and E. Annexure A explains details of principle critical stress for other walls. Annexure B gives details of maximum top displacement for other walls. Annexure C shows the summary of principle critical stress for other zones. Annexure D presents the summary of maximum top displacement for other soil profile types. Annexure E gives Guidelines for designers to follow for design of brick masonry structures. Annexure F is the proposed RC vertical and horizontal stiffeners (with FPS details) using a diagonal approach for remaining combinations of seismic parameter. Annexure G is the joint details of vertical and horizontal stiffeners.

CHAPTER 2

LITERATURE REVIEW

2.1 Background

The unreinforced brick masonry structures are seismically vulnerable to earthquake. In order to make them earthquake-resistant, the use of concrete stiffeners in brick masonry structures is one possible solution. Alternative option for earthquake-resistant structures is moment-resisting frames structures. In these structures, the columns and beams are allowed to bend, but the joints or connectors between them are rigid (Harris 2013). Engineers and seismologists have favored base isolation for years as a means to protect buildings during an earthquake. Base isolation involves floating of a building above its foundation on a system of bearings, springs or padded cylinders (Harris 2013). Another tried-and-true technology to help buildings stand up to earthquakes is shock absorber. Shock absorbers slow down and reduce the magnitude of vibratory motions by turning the kinetic energy of your bouncing suspension into heat energy that can be dissipated through hydraulic fluid (Harris 2013). Nowadays engineers refer to a system known as tuned mass dampers for earthquake-resistant structures. The job of a tuned mass damper is to counteract resonance and to minimize the dynamic response of the structure (Harris 2013). 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) and (2013). However, this technique needs to be validated for 3D structure before implementation. Hence, the behavior of masonry structures during real earthquake, experimental testing and numerical modelling of masonry are discussed in detail in this chapter.

2.2 Unreinforced and reinforced brick masonry structures (UBMS and RBMS)

The masonry is oldest and widely used construction method (Olivito and Stumpo 2001, Kamal *et al.* 2014, Rabinovitch and Madah 2011). Brick masonry structural elements are also abundant in historic buildings (Drougkas *et al.* 2016). In the world, unreinforced masonry buildings are one of the most seismically vulnerable structure types (Spence 2007). The losses of property and human lives were due to the collapse of such structures during earthquakes. These structures were usually designed for gravity loads only (Naseer *et al.* 2010). These structures were generally constructed from the traditional materials. These materials are 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). A French contractor and structural engineer, Paul Cottancin, proposed stiffeners to strengthen the masonry buildings at the end of 20th century (Edgell 1985). The behavior of masonry structures are studied under earthquake loadings in laboratory by many researchers. For example, substantial nonlinear behavior was observed for unreinforced masonry structures, when tested under time-scaled Nahnni earthquake 1985 (Abram 2000). 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). The increment was not only at yield but also at the ultimate state. The bond between mortar and bricks also plays an important role in overall strength of masonry. The brick masonry made with less absorptive brick would have much more shear as well as tensile bond strength compared to the masonry made with highly absorptive brick units (Calvi *et al.* 1996).

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). The reason is that proper construction techniques were being followed in Chile (Dilley *et al.* 2005). 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). On the other hand, the confined masonry houses performed well in this earthquake (EERI 2006). Therefore, it can be claimed from the previous studies that both horizontal and vertical stiffeners, are necessary for resisting combination of lateral and gravity loadings in brick masonry structures.

The current practice is to use generalized cross-section of stiffeners in reinforced brick masonry structure (RBMS) considering broader seismic parameters. Table 2.1 presents quantization of reinforcement magnitude of vertical stiffeners by Amjad (2009) considering seismic demand taking into account peak ground acceleration for different number of stories. It is worth noting that steel grade is not clearly stated, it can be either grade 40 or grade 60. In addition to this, only three diameters of steel re-bars i.e. #2, #3 and #4 are used. For low seismic demand, there is no difference in magnitude of steel reinforcement for two and four stories structures. In case, if it is assumed that re-bars 4-#2 are sufficient for four stories structure, then this reinforcement is much more for two stories structure. If it is assumed that re-bars 4-#2 is adequate for two stories structure then it is not suitable for four stories structure (4-#3 may be ample). Similarly, no difference is adopted in magnitude of steel reinforcement for two, four and six stories structures.

Table 2.1: Re-bar quantization for vertical stiffeners by Amjad (2009) (FPS system)

No. of stories	Re-bars up to stories	Seismic demand		
		Low (PGA = 0.1 g)	Moderate (0.1 g < PGA < 0.2 g)	High (0.2 g < PGA < 0.4 g)
2	1-2	4-#2	4-#3	4-#4
4	1-2	4-#2	4-#3	4-#4
	3-4	4-#2	4-#3	4-#4
6	1-2	4-#3	4-#4	4-#4
	3-4	4-#2	4-#3	4-#4
	5-6	4-#2	4-#3	4-#4

On the other hand, Arya *et al.* (2012) considered: (i) building categories for quantization of mortar, (ii) combination of building categories and span for quantization of horizontal stiffeners and (iii) combination of building categories and number of stories for quantization of vertical stiffeners. The number of stories can be regarded as an equivalent parameter of time period because period is a direct function of building height in many empirical relations. According to them, there are four seismic zones (A=widespread collapse/destruction, B=collapse/heavy damage, C=damage and D=minor damage), four soil profile types (hard, medium, soft and weak) and two importance factors (ordinary and important). Only three seismic zones (A, B and C), two soil profile types (soft and medium to hard) and two importance factors (ordinary and important) are considered for making 11 combinations to further define four building categories as presented in Table 2.2. It is important to note that the combination of zone C, ordinary building and medium to hard soil is not considered. Similarly, zone D is not considered at all. This may be taken as perhaps stiffeners are not required for these parameters. The design quantization for different items is listed in Table 2.3. The same kinds of observations, about reinforcement magnitude as done for Table 2.1, prevail for Table 2.3. For example, (i) same reinforcement i.e. 2-#3 is recommended for 5 m span of horizontal stiffener for building categories II, III and IV and (ii) the same reinforcement i.e. 1-#5 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 the 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 non-engineered practices of brick masonry structures in developing countries are shown in Figure 2.1. The horizontal stiffeners are missing in house #1 and #4. The vertical stiffeners are missing in house #2. In house #3 and #4, the vertical stiffeners are missing at the critical location i.e. at corners. The stiffeners should be provided at the appropriate locations in order to make brick masonry structures more earthquake-resistant. The locations of stiffeners within a brick masonry structures are very well established by many researchers. Generally, the stiffeners are provided at corners, at wall junctions and around openings (EERI and IAEE 2011, Arya *et al.* 2012). During earthquakes, cracks often initiate because of unsymmetry due to imbalance in the sizes and positions of openings in the walls. Openings in the wall are necessary for providing ventilation using doors and windows. But larger and number of openings make the wall weak. Therefore, the number and size of openings should be limited and centrally located.

Table 2.2: Combinations for defining building category by Arya *et al.* (2012)

Building category	Combination for the category		
	Seismic zone	Building	Soil profile type
I	A	Important	Soft
II	A	Important	Medium to hard
	A	Ordinary	Soft
	B	Important	Soft
III	A	Ordinary	Medium to hard
	B	Important	Medium to hard
	B	Ordinary	Soft
	C	Important	Soft
IV	B	Ordinary	Medium to hard
	C	Important	Medium to hard
	C	Ordinary	Soft

Table 2.3: Design quantization for different items by Arya *et al.* (2012) (FPS system)

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 - #4	2 - #3	2 - #3	2 - #3
	6 m span	2 - #5	2 - #4	2 - #3	2 - #3
	7 m span	2 - #5	2 - #5	2 - #4	2 - #3
Reinforcement for vertical stiffener at ground floor	1 storey	1 - #5	1 - #4	1 - #4	NIL
	2 stories	1 - #6	1 - #5	1 - #5	NIL
	3 stories	1 - #6	1 - #5	1 - #5	NIL
	4 stories	Building not allowed		1 - #5	1 - #4

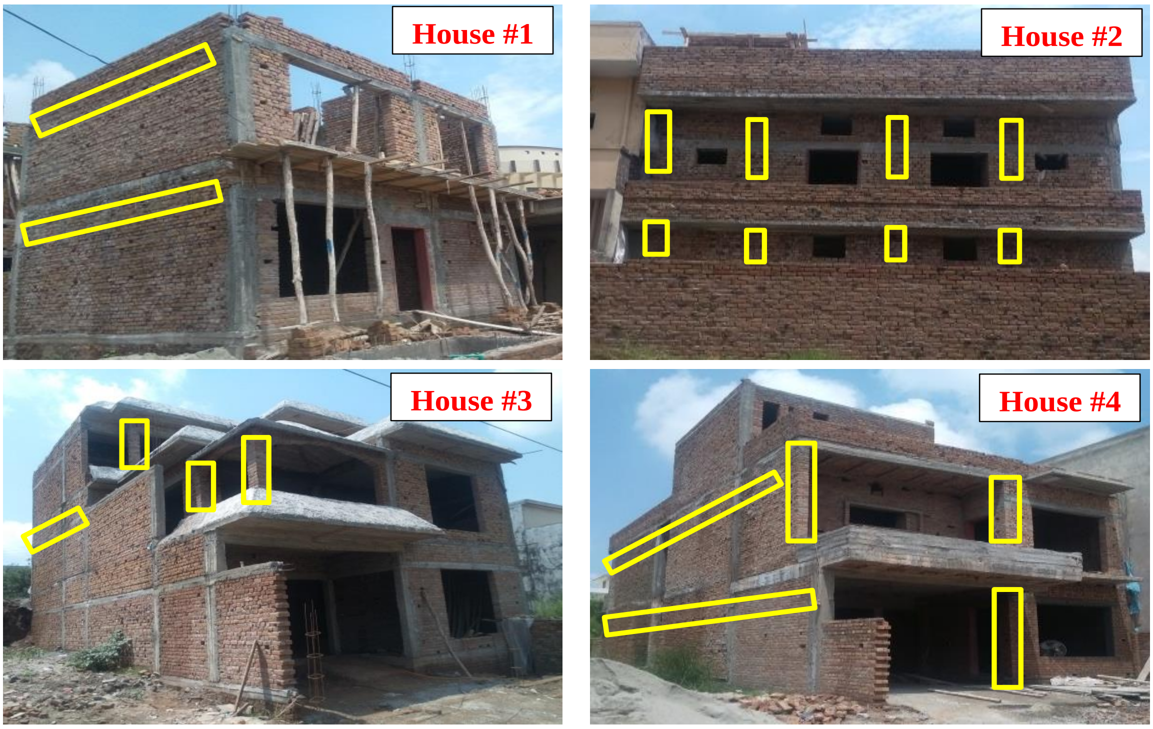


Figure 2.1: Un-engineered practice of brick masonry structures in developing countries

2.2.1 Guidelines for reinforced brick masonry structures (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. It may be noted that the brick size 9" x 4.5" x 3" is standard size and the actual size is little less (approximately 8.5" x 4" x 2.5", assuming 0.5" 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: 4.5" x 4.5" x 3", 9" x 2.25" x 3", 6.75" x 4.5" x 3" and 2.25" x 4.5" x 3" 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 4.5” and 3”, 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 4.5” and 3”, 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.

2.3 Numerical modelling technique of brick masonary

Lourence (1996) and Sandoval and Arnau (2016) 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. In macro numerical modelling, the masonry material components are lumped considering it as a homogeneous material with anisotropic or isotropic mechanical properties. The simplified micro numerical models consider the unit-mortar interface as an individual element with distinct properties, and the mechanical characteristic of mortar and masonry units are lumped in the same element. The detailed micro numerical modelling considers mortar, masonry units and unit-mortar interface as distinct elements with different properties. 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. For each load step, the principal stress and strain values were computed which directly relates to the model through a relation. The relation described the behavior of material in compression, shear and tension after the crack appeared. The crack pattern at the maximum displacement was observed and force-displacement curves were produced. It was observed that the numerical model was capable of detecting the major features of experimental behavior of tested walls. Marques and Lourenço (2014) investigated the confined and unreinforced masonry structures to validate experimental results under seismic loading. The macro-element model was developed in 3D macro software and cracking behavior against displacement was observed. The unreinforced brick masonry was severely damaged against 10 mm displacement while the confined masonry showed widespread cracking with controlled damage. The results of numerical analysis were in good agreement with that of experimental work. Okail *et al.* (2016) investigated the numerical model of confined brick masonry walls using finite element method to validate the behavior in light of experimental results. The load verses top lateral wall displacement curves were obtained for solid walls and walls with opening. It was observed that finite element model shows the satisfactory results against the structural behavior of tested walls. Shariq *et al.* (2008) performed a numerical study on seismic performance of masonry walls with different openings conditions. A single story masonry room subjected to seismic force in various directions was evaluated with finite element analysis for different wall openings and different aspect ratios. The response spectrum method was applied for analysis. The maximum shear stresses were observed in longitudinal walls and the maximum principle tensile stresses were observed in transverse walls. The maximum stresses developed along the opening of transverse wall of room for critical direction of seismic force.

The material properties used by different researchers for numerical modelling of brick masonry are elastic modulus (E) and poison ratio (ʋ). The range of E and ʋ are 1.5-2.5 GPa and 0.13-0.15, respectively, as shown in Table 2.4. But Koutromanos *et al.* (2011) reported E of 18.5 GPa. However for this current study, E and ʋ of 1.5 GPa and 0.15, respectively, are used because it is also reported by Ignatakis and Kosmas (2009), Mohammed (2010), Karantoni (2012) and Tavlopoulou et al. (2015).

2.3.1 Macro modelling technique

Tavlopoulou *et al.* (2015) performed a parametric study about the seismic behavior of superstructure of unreinforced masonry building. A full 3D detailed model of the building under static and dynamic loading scenarios were developed. The assumption of different hypothesis was made for the interconnection between the two existing materials (masonry and reinforced concrete one). The supposition is also made between the core and the external walls on the architectural proposal of reuse.

Table 2.4: Material properties used for brick masonry modeling by different researchers

Elastic Modulus (E) (GPa)	Poisons Ratio (v) (-)	Remarks
18.5	-	Koutromanos *et al.* (2011)
2.5	0.13	Medeiros *et al.* (2013)
1.6	-	Giamundo *et al.* (2014)
1.5	0.15	Ignatakis and Kosmas (2009), Mohammed (2010), Karantoni (2012) and Tavlopoulou *et al.* (2015).
1.5	0.15	Current study

Figure 2.2: Macro numerical model in SAP2000 by Tavlopoulou *et al.* (2015)

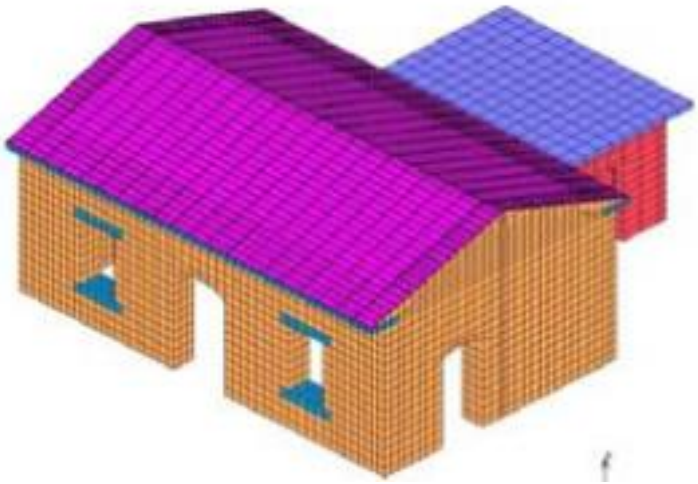
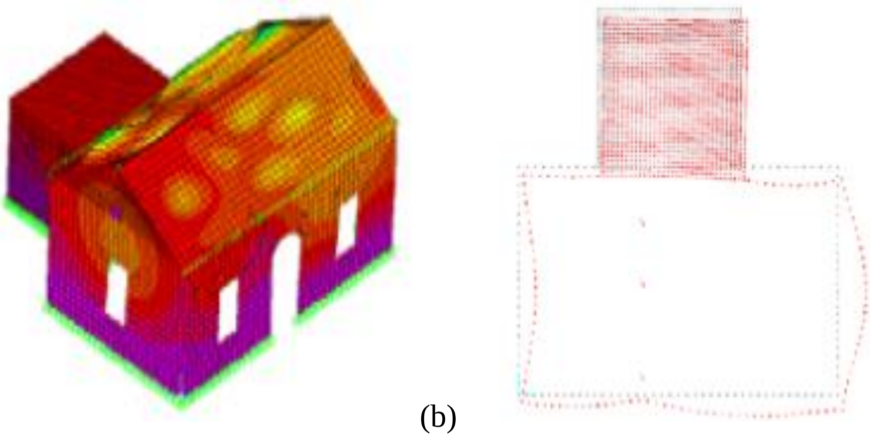


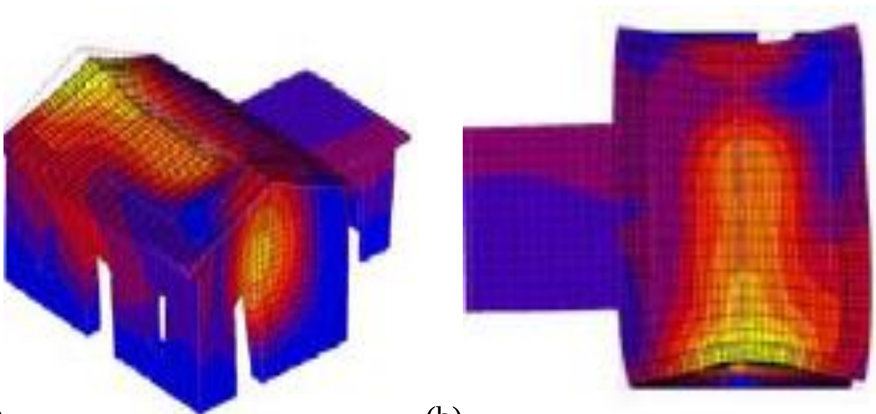
Figure 2.3: Macro numerical model in MARC Mentat by Tavlopoulou *et al.* (2015)

For modeling and analysis, the SAP and MARC Mentat finite element softwares, were used. The macro models of superstructure are developed in SAP and MARC Mentat by Tavlopoulou *et al.* (2015) and are shown in Figure 2.2 and 2.3, respectively. The deformed shape of superstructure in SAP2000 and MARC Mentat are Figure 2.4 and 2.5, respectively. The same material properties (i.e. elastic modulus and poison ratio) shown in Table 2.4 were used in both software's. The most stressed sides are the smaller ones and especially the areas above the openings. The plan rotation is also observed. The displacements verses height graphs were made for the comparison between software's. From the analysis it was concluded that critical areas relates with increased stress concentration near the lintel of the openings.



(a) (b)

Figure 2.4: Deformed structure in SAP2000 by Tavlopoulou *et al.* (2015): (a) three dimensional view (b) plan



(a) (b)

Figure 2.5: Deformed structure in MARC Mentat by Tavlopoulou et al. (2015): (a) three dimensional view (b) plan

2.4 Summary

It can be claimed from the previous studies that both horizontal and vertical stiffeners are absolute necessary for resisting the combination of lateral and gravity loadings in brick masonry structures. 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. To the best of author's knowledge, RC stiffeners design is not precisely optimized for seismic demands considering all seismic factors. For many engineering applications, the use of macro numerical models are recommended.

CHAPTER 3

DESIGN OPTIMIZATION USING A DIAGONAL APPROACH

3.1 Background

A diagonal approach is selected for finalizing the design output of vertical and horizontal stiffeners for different combinations of seismic zones and soil profile types. This can be judged easily from the selected color scheme presented in Figures 3.1 and 3.2. It may be noted that the concept of diagonal approach for design output of vertical and horizontal stiffeners is proposed by Engr. Dr. Majid Ali. A particular color is used for a combination of a specific design output i.e. concrete strength, concrete cross-section, steel grade, number/diameter of longitudinal re-bar and spacing/diameter of transverse re-bars. Different shades of same color are used for same concrete strength, concrete cross-section and steel grade. When one or two of these parameters is changed, a different color is selected. This makes it easy to understand the adopted diagonal approach showing the minute differences in design output. There are five seismic zones and five soil profile types, making a matrix of 5 x 5. Four colors are selected, yellow (three shades), brown (two shades), green (three shades) and pink (one shade) in Figures 2 and 3. For yellow color, concrete cross-section, concrete strength and steel grade remain same, only diameter of re-bars varies within yellow shades. For a shift from yellow to brown color, only steel grade changes from grade 280 to grade 420. Within brown shades, only diameter of re-bars varies. For a shift from brown to green color, larger concrete cross-section and high concrete strength along with decreased steel grade is used. Within green shades, there is a change in diameter of longitudinal re-bars and spacing of transverse re-bars. For a shift from green to pink color, only higher steel grade for longitudinal re-bars is changed.

3.2 Diagonal approach for proposed design of RC vertical stiffeners

The summary of the proposed design of reinforced concrete (RC) vertical stiffeners is presented in Figures 3.1 for different seismic zones and soil profile types with I=1 and T $\leq$ 0.7 s. For design of vertical stiffeners (Figure 3.1), 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 for concrete cross-section 230 mm x 230 mm with grade 280 longitudinal re-bars and ϕ10- 115 mm/230 mm for concrete cross-section 230 mm x 230 mm with grade 420 longitudinal re-bars. It may be noted that ties ϕ6- 115 mm/230 mm means ϕ6-115 mm shall be used within both upper and lower quarter height and ϕ6-230 mm shall be used with in middle half height of the vertical stiffener.

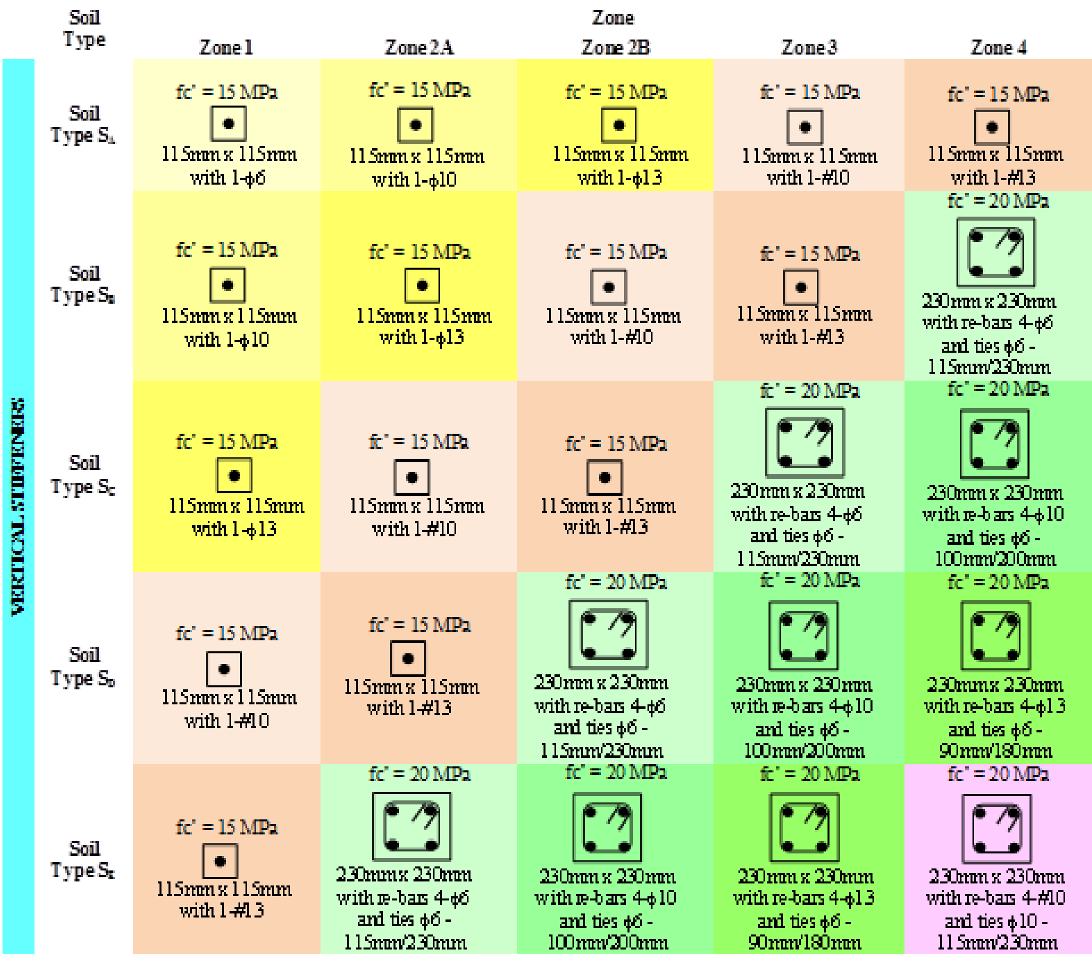


Figure 3.1: Cross-sectional details of RC vertical stiffeners for different seismic zones and soil profile types with I = 1 and T $\leq$ 0.7s

3.3 Diagonal approach for proposed design of RC horizontal stiffeners

The summary of the proposed design of RC horizontal stiffeners is presented in Figures 3.2 for different seismic zones and soil profile types with I=1 and T $\leq$ 0.7 s.

For design of horizontal stiffeners (Figure 3.2), 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. 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.

HORIZONTAL STIFFENERS

Soil Type	Zone 1	Zone 2A	Zone Zone 2B	Zone 3	Zone 4
Soil Type S_A	fc' = 15 MPa 230mm x 75mm with re-bars 2-ϕ6 and stirrups ϕ6 - 200mm	fc' = 15 MPa 230mm x 75mm with re-bars 2-ϕ10 and stirrups ϕ6 - 150mm	fc' = 15 MPa 230mm x 75mm with re-bars 2-ϕ13 and stirrups ϕ6 - 100mm	fc' = 15 MPa 230mm x 75mm with re-bars 2-#10 and stirrups ϕ10 - 200mm	fc' = 15 MPa 230mm x 75mm with re-bars 2-#13 and stirrups ϕ10 - 150mm
Soil Type S_B	fc' = 15 MPa 230mm x 75mm with re-bars 2-ϕ10 and stirrups ϕ6 - 150mm	fc' = 15 MPa 230mm x 75mm with re-bars 2-ϕ13 and stirrups ϕ6 - 100mm	fc' = 15 MPa 230mm x 75mm with re-bars 2-#10 and stirrups ϕ10 - 200mm	fc' = 15 MPa 230mm x 75mm with re-bars 2-#13 and stirrups ϕ10 - 150mm	fc' = 20 MPa 230mm x 150mm with re-bars 4-ϕ6 and stirrups ϕ6 - 200mm
Soil Type S_C	fc' = 15 MPa 230mm x 75mm with re-bars 2-ϕ13 and stirrups ϕ6 - 100mm	fc' = 15 MPa 230mm x 75mm with re-bars 2-#10 and stirrups ϕ10 - 200mm	fc' = 15 MPa 230mm x 75mm with re-bars 2-#13 and stirrups ϕ10 - 150mm	fc' = 20 MPa 230mm x 150mm with re-bars 4-ϕ6 and stirrups ϕ6 - 200mm	fc' = 20 MPa 225mm x 150mm with re-bars 4-ϕ10 and stirrups ϕ6 - 150mm
Soil Type S_D	fc' = 15 MPa 230mm x 75mm with re-bars 2-#10 and stirrups ϕ10 - 200mm	fc' = 15 MPa 230mm x 75mm with re-bars 2-#13 and stirrups ϕ10 - 150mm	fc' = 20 MPa 230mm x 150mm with re-bars 4-ϕ6 and stirrups ϕ6 - 200mm	fc' = 20 MPa 230mm x 150mm with re-bars 4-ϕ6 and stirrups ϕ6 - 200mm	fc' = 20 MPa 230mm x 150mm with re-bars 4-ϕ13 and stirrups ϕ6 - 100mm
Soil Type S_E	fc' = 15 MPa 230mm x 75mm with re-bars 2-#13 and stirrups ϕ10 - 150mm	fc' = 20 MPa 230mm x 150mm with re-bars 4-ϕ6 and stirrups ϕ6 - 200mm	fc' = 20 MPa 230mm x 150mm with re-bars 4-ϕ6 and stirrups ϕ6 - 200mm	fc' = 20 MPa 230mm x 150mm with re-bars 4-ϕ13 and stirrups ϕ6 - 100mm	fc' = 20 MPa 230mm x 150mm with re-bars 4-#10 and stirrups ϕ10 - 200mm

Figure 3.2: Cross-sectional details of RC horizontal stiffeners for different seismic zones and soil profile types with I = 1 and T $\leq$ 0.7s

The guidelines for designers to follow during design of brick masonry structures are shown in Annexure E (refer Annexure E1, E2, E3 and E4).The cross-sectional details of RC vertical and horizontal stiffeners for different seismic zones and soil profile types with $I = 1$ and $T < 0.7$s with FPS details are shown in Figure F1. The joint details of vertical and horizontal stiffeners are shown in Annexure G.

3.4 Summary

The concept of vertical and horizontal stiffeners is proposed using a diagonal approach for all seismic zones and all soil profile types with $I = 1$ and $T \leq 0.7$s. This approach needs to be validated numerically.

CHAPTER 4

NUMERICAL MODELLING OF UBMS AND RBMS

4.1 Background

The proposed design of RC vertical and horizontal stiffeners has already been explained in sections 3.2 and 3.3, respectively, with different seismic parameters. The numerical model is developed in software according to the guidelines mentioned in section 2.3. The selection of brick masonry house, location of vertical stiffeners and numerical modelling are described in this chapter.

4.2 Selection of house and location of stiffeners

A simple house to be constructed as brick masonry is considered. The first task is to locate the vertical stiffeners. Many studies have provided the guidelines for the location of vertical stiffeners as explained earlier in the introduction section. Figure 4.1(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 color (12 numbers). The stiffeners at second important locations are shown in cyan color (7 numbers). The stiffeners with relatively less important locations are shown in green color (6 numbers). At this stage, the question arises whether these numbers of vertical stiffeners can be reduced or not. Usually, the vertical stiffeners are provided at corners, at junctions and around openings (doors and windows). 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”. Following this priority, vertical stiffeners around openings are removed and ground floor plan with reduced number of stiffeners (i.e. with 19 vertical stiffeners) is shown in Figure 4.1(b). Figure 4.1(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 study, house with 19 vertical stiffeners is considered.

4.3 Macro modelling of selected house as UBMS and RBMS

A three dimensional geometrical model of superstructure of considered brick masonry structure is developed in SAP2000. The macro modelling technique is used for modelling because of the reasons discussed in the section 2.3. The architectural plans of all levels, original structure under construction and SAP model are shown in

Figure 4.2. The elastic modulus and poison ratio in current study are 1.5 GPa and 0.15, respectively. The range of R is from 4 to 6.4 reported by Shedid *et al.* (2011).

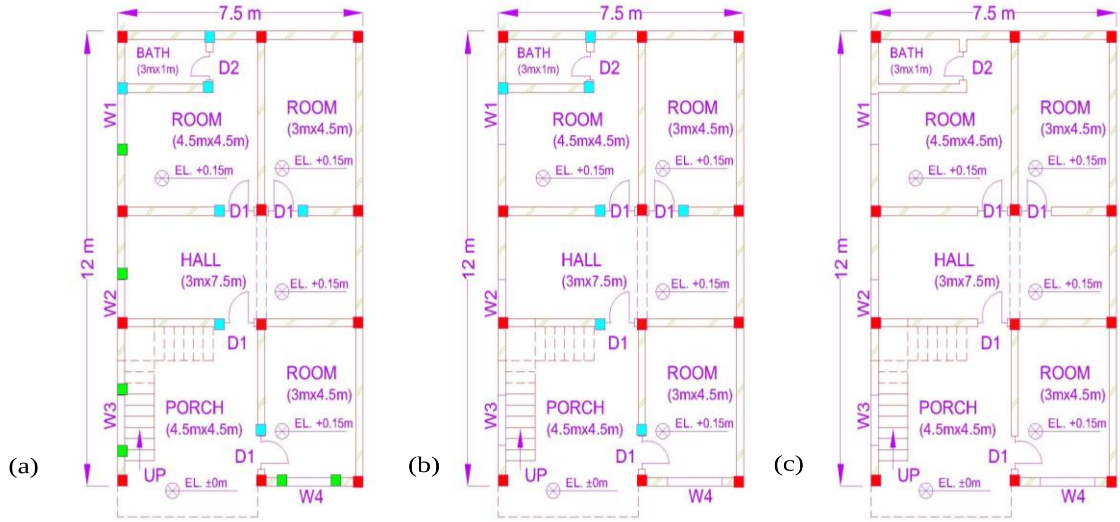


Figure 4.1: Proposed vertical stiffeners for considered ground floor (a) at 25 locations (b) at 19 locations (c) at 12 locations

The boundary condition at the bottom of the walls is hinged support because Shiga *et al.* (1980) and Ranjbaran *et al.* (2012) defined boundary condition as a hinged support at the bottom in macro model of brick masonry. The thickness of all walls in UBMS and RBMS is 230 mm. The longitudinal walls (e.g. walls 1, 2 and 2a) are 12 m long while transverse wall (e.g. walls 3, 3a and 4) are 7.5 m long. The height of walls with and without mumty is 9 m and 7 m, respectively. The UBMS consists of walls only while the RBMS consists of walls in addition to RC vertical and horizontal stiffeners. The various stiffener's configurations i.e. cross-section, concrete strength and re-bars are used for different seismic parameters as mentioned in Figures 3.1 and 3.2. The models are developed according to the given architectural plan as shown in Figure 4.2(a) and the SAP macro model is shown in Figure 4.2(c).

Mainly, two models of superstructure of brick masonry houses are developed i.e. unreinforced brick masonry structure (UBMS) and reinforced brick masonry structure (RBMS) with different configuration of RC stiffeners. From these two models, a total of 50 models are generated i.e. 25 for UBMS and 25 for RBMS. These models are evaluated for different combinations of seismic parameters (mainly, soil profile types and seismic zones are variable). The analyses are performed for all seismic zones (zone 1, zone 2A, zone 2B, zone 3 and zone 4) and for all soil profile types (SA, SB, SC, SD and SE) with R = 5.5 and I = 1. The time period in all models is < 0.7s. The results of different RBMS are compared with that of UBMS.

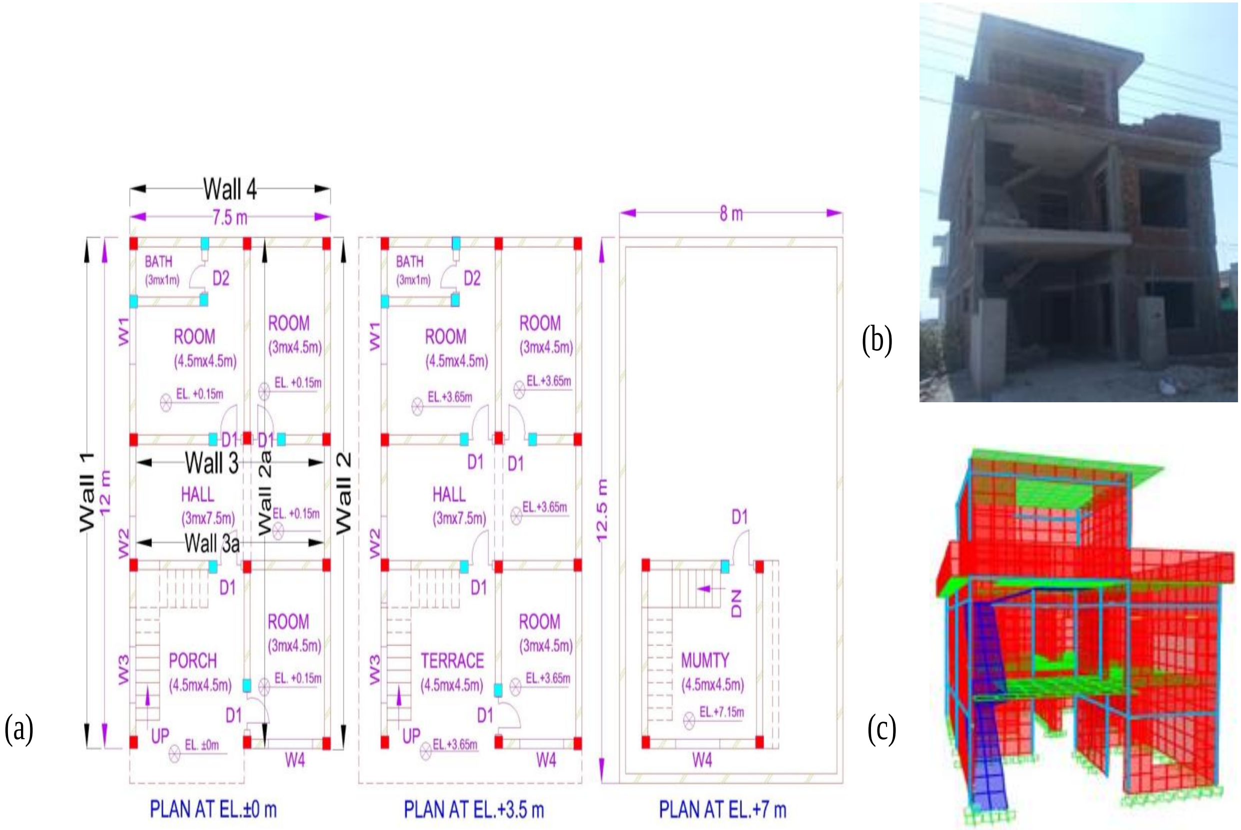


Figure 4.2: Under construction building (a) architectural plans of all levels (b) original structure under construction (c) three dimensional geometrical SAP model

4.4 Summary

The vertical stiffeners locations are selected keeping in mind the safety and economy. The priority is set in a sequence of “at corner”, “at junction”, “around doors” and finally “around windows”. The vertical stiffeners around openings are removed and macro numerical model with reduced number of stiffeners is developed. The macro numerical model of UBMS and RBMS are developed in SAP2000 according to the given architectural plans of all levels in Figure 4.2(a). The analysis for UBMS and RBMS are performed for all soil profile types and all seismic zones and is discussed in next chapter.

CHAPTER 5

RESULTS AND ANALYSIS OF SEISMIC PERFORMANCE

5.1 Background

The macro numerical models of selected house are developed in SAP2000 Four walls are considered for the explanation of detail analysis of seismic performance: the longitudinal wall with openings (wall 1), longitudinal solid wall (wall 2), transverse wall with opening (wall 3) and transverse solid wall (wall 4). The principal critical stress and maximum top displacement (in-plane) are studied in details for evaluating seismic performance and finally diagonal approach is defined using these two parameters. The predication of crack propagation is also made.

5.2 Principle critical stress (PCS) in UBMS and RBMS

The shell element stresses are the forces-per-unit-area that acts within the volume of the element to resist the loading (SAP2000 1998). 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). For current research, the shear stresses against absolute envelop are taken as PCS because these are critical.

5.2.1 PCS in longitudinal wall with openings

The PCS in longitudinal wall with openings (wall 1) of UBMS and RBMS for seismic zone 2B and all soil profile types are shown in Figure 5.1.It is noted that PCS in wall 1 of UBMS and RBMS for soil profile type SA is 1.68 N/mm^2 and 1.19 N/mm^2, respectively. The PCS in wall 1 of RBMS is decreased by 29% as compared to that of UBMS. The reason for decreased PCS in wall 1 of RBMS is the provision of vertical and horizontal stiffeners (V.S and H.S, respectively), creating confinement effect in brick masonry wall. For soil profile type SB, the PCS in wall 1 is 1.74 N/mm^2 and 1.21 N/mm^2 for UBMS and RBMS, respectively. There is a decrease of 30% for PCS in wall 1 of RBMS compared to that of UBMS. The PCS in wall 1 for soil profile type SB is increased by 4% in UBMS and 2% in RBMS as compared to that for soil profile type SA. According to UBC 97, the soil profile types SA and SB are hard rock and rock, respectively, therefore the PCS in wall 1 of both UBMS and RBMS for soil profile type SA are less than that for soil profile type SB. In wall 1 of UBMS, the PCS is 1.78 N/mm^2 and in RBMS it is 1.27 N/mm^2 for soil profile type

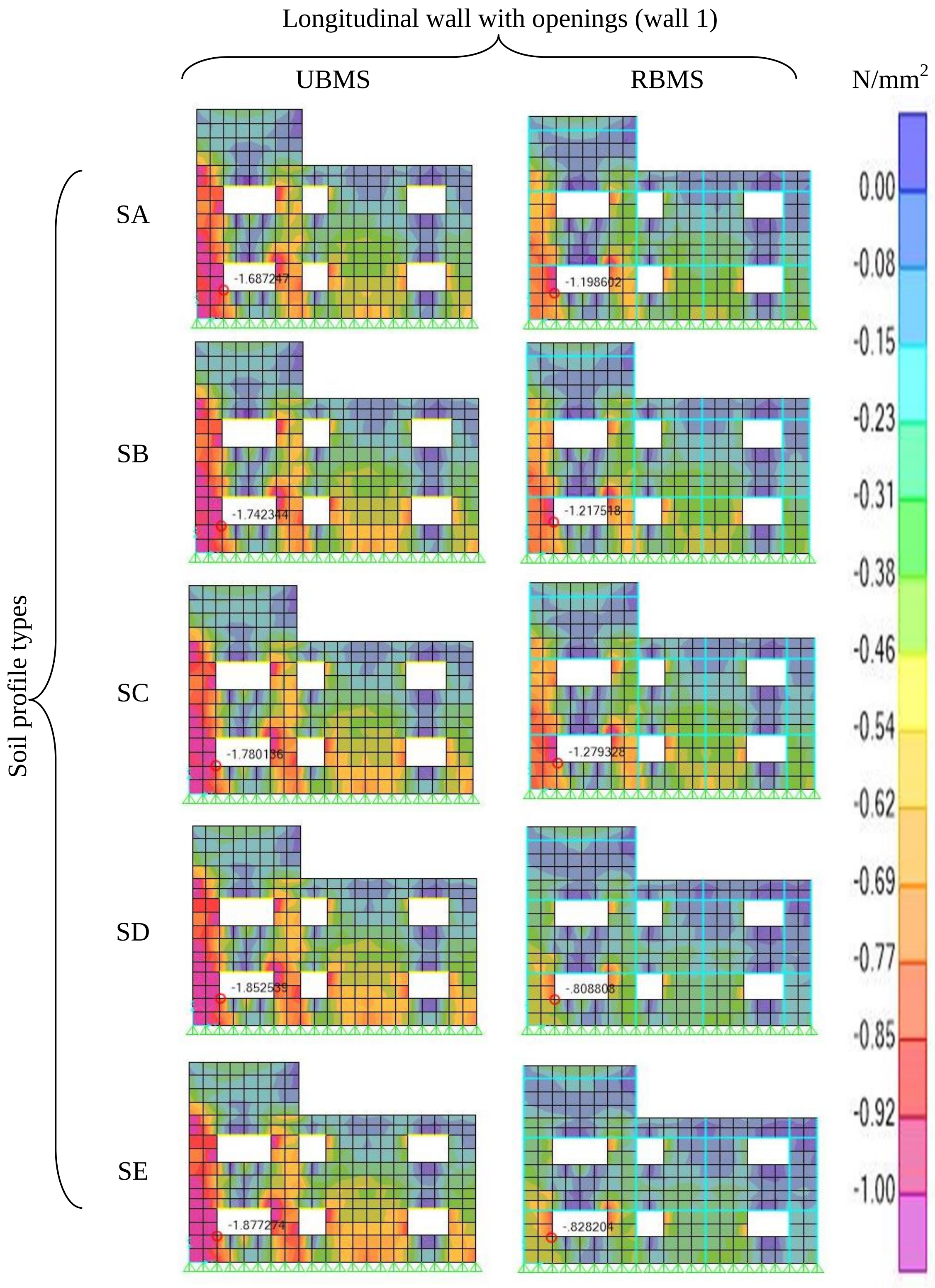


Figure 5.1: Principle critical stress in longitudinal wall with openings (wall 1) for seismic zone 2B and all soil profile types

SC. For soil profile type SC, the PCS in wall 1 of RBMS is reduced by 29% with respect to that of UBMS. The PCS in wall 1 for soil profile type SC is increased by 2% and 5% in UBMS and RBMS, respectively, compared to that for soil profile type SB. These increments are 6% and 7%, respectively, when compared with that for soil profile type SA. The soil profile types SB and SC are rock and stiff soil according to UBC 97; hence the PCS in UBMS and RBMS for soil profile type SB is less than that for soil profile type SC. The PCS is reduced in RBMS because of the reason as explained earlier. For soil profile type SD, the PCS in wall 1 is 1.85 N/mm^2 for UBMS and 0.80 N/mm^2 for RBMS. Thus, the PCS in wall 1 of RBMS is decreased by 57% compared to that of UBMS. The PCS in wall 1 of UBMS is increased for soil profile type SD by 4% and in RBMS it is decreased by 37% compared to that for soil profile type SC. There is 10% increment and 33% decrement for PCS in wall 1 of UBMS and RBMS, respectively, for soil profile type SD when compared with that for soil profile type SA. The increment in PCS for soil profile type SD compared to SC for UBMS is due to the fact that SD is stiff soil while SC is soft rock and very dense soil (UBC 97). The PCS in wall 1 of RBMS is reduced for soil profile type SD due to the increased cross-section, concrete strength and steel re-bar of V.S and H.S. The PCS in wall 1 for soil profile type SE is 1.87 N/mm^2 and 0.82 N/mm^2 for UBMS and RBMS, respectively. This is a decrease of 56% for PCS in wall 1 of RBMS compared to that of UBMS. For soil profile type SE, the PCS is increased by 1% and 3% in wall 1 of UBMS and RBMS, respectively, compared to that for soil profile type SD. For soil profile type SE, the PCS is increased by 11% in wall 1 of UBMS and decreased by 31% in wall 1 of RBMS as compared to that for soil profile type SA. UBC 97 reported that the soil profile types SD and SE are stiff and soft soils, respectively, therefore the PCS in wall 1 of UBMS and RBMS is more for soil profile type SE. As expected, the PCS in wall 1 of UBMS is generally increased with changing soil profile types from SA to SE. In wall 1 of RBMS, the PCS is also increased for soil profile types from SA to SC. The PCS in wall 1 of RBMS for soil profile types SD and SE is decreased as compared to that for soil profile type SA. The reason for decrement is the larger cross-sections of stiffeners i.e. V.S of 230 mm x 230 mm and H.S of 230 mm x 150 mm. Even with same cross-section of stiffeners and higher reinforcement, the PCS in wall 1 of RBMS is increased when soil profile type is changed from SD to SE.

5.2.2 PCS in longitudinal solid wall

As shown in Figure 5.2, the PCS in longitudinal solid wall (wall 2) of UBMS and RBMS for soil profile type SA is 0.71 N/mm^2 and 0.48 N/mm^2, respectively. The PCS in wall 2 of RBMS is decreased by 32% as compared to that of UBMS. For soil profile type SB, the PCS in wall 2 is 0.75 N/mm^2 and 0.51 N/mm^2 for UBMS and RBMS, respectively. This is a decrease of 32% for PCS in wall 2 of RBMS compared

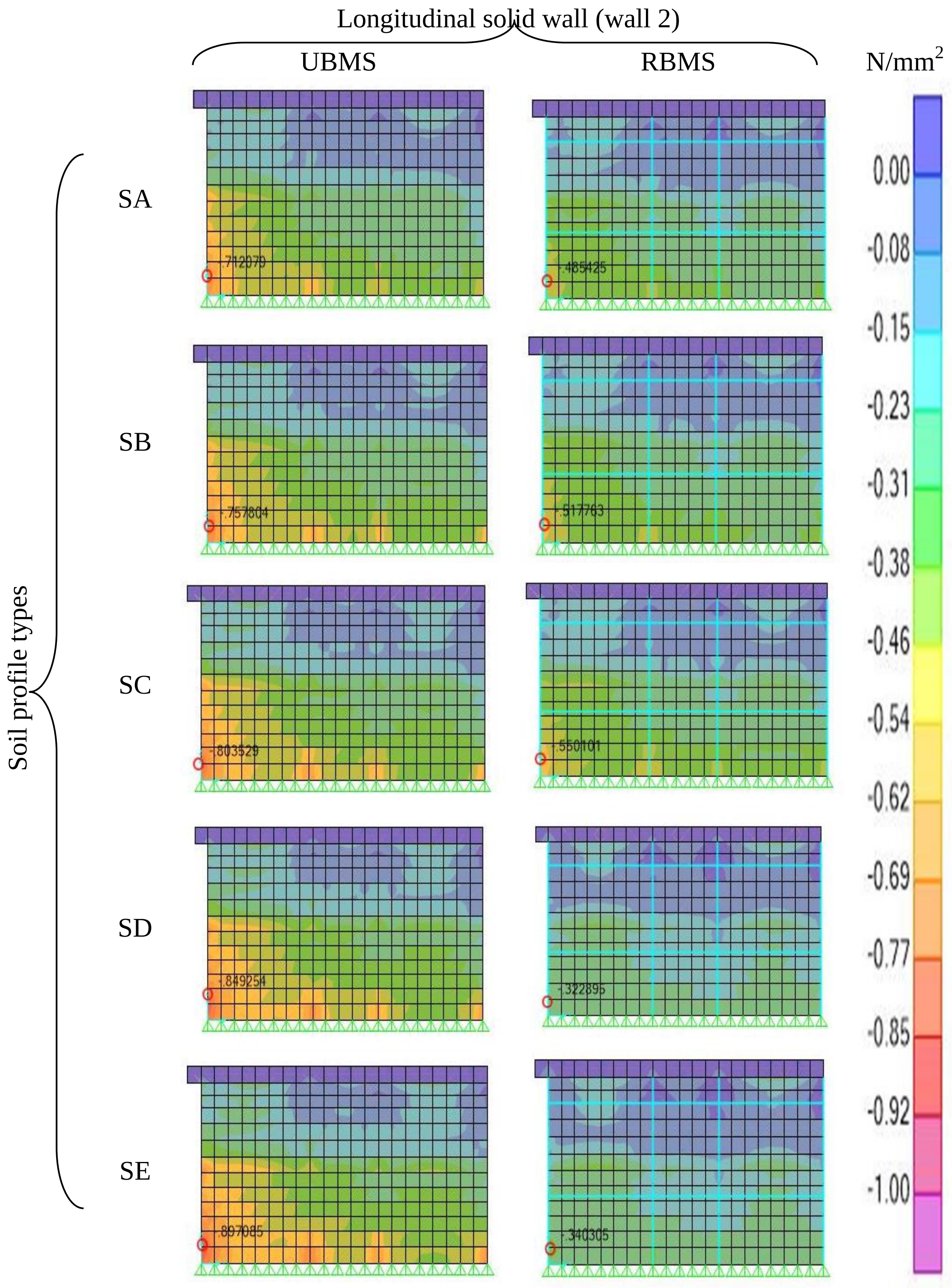


Figure 5.2: Principle critical stress in longitudinal solid wall (wall 2) for seismic zone 2B and all soil profile types

to that of UBMS. The PCS in wall 2 for soil profile type SB is increased by 6% both in UBMS and RBMS as compared to that for soil profile type SA. In wall 2 of UBMS, the PCS is 0.80 N/mm^2 and in RBMS it is 0.55 N/mm^2 for soil profile type SC. For soil profile type SC, the PCS in wall 2 of RBMS is reduced by 31% with respect to that of UBMS. The PCS in wall 2 for soil profile type SC is increased by 7% and 8% in UBMS and RBMS, respectively, compared to that for soil profile type SB. These increments are 13% and 15%, respectively, when compared with that for soil profile type SA. For soil profile type SD, the PCS in wall 2 is 0.84 N/mm^2 for UBMS and 0.32 N/mm^2 for RBMS. Thus, the PCS in wall 2 of RBMS is decreased by 62% compared to that of UBMS. The PCS in wall 2 of UBMS is increased for soil profile type SD by 5% and in RBMS it is decreased by 45% compared to that for soil profile type SC. There is 18% increment and 33% decrement for PCS in wall 2 of UBMS and RBMS, respectively, for soil profile type SD when compared with that for soil profile type SA. The PCS in wall 2 for soil profile type SE is 0.89 N/mm^2 and 0.34 N/mm^2 for UBMS and RBMS, respectively. This is a decrease of 62% for PCS in wall 1 of RBMS compared to that of UBMS. For soil profile type SE, the PCS are increased by 6% in wall 2 of both UBMS and RBMS, respectively, compared to that for soil profile type SD. For soil profile type SE, the PCS is increased by 25% in wall 2 of UBMS and decreased by 29% in wall 2 of RBMS as compared to that for soil profile type SA. As expected again, the PCS in wall 2 of UBMS is generally increased with changing soil profile types from SA to SE. In wall 2 of RBMS, the PCS is also increased for soil profile types from SA to SC. The PCS in wall 2 of RBMS for soil profile types SD and SE is decreased as compared to that of soil profile type SA. Even with same cross-section of stiffeners and higher reinforcement, the PCS in wall 2 of RBMS is increased when soil profile type is changed from SD to SE.

5.2.3 PCS in transverse wall with opening

The PCS in transverse wall with opening (wall 3) of UBMS are 0.61 N/mm^2, 0.66 N/mm^2, 0.72 N/mm^2, 0.77 N/mm^2 and 0.84 N/mm^2 for soil profile types SA, SB, SC, SD and SE, respectively (refer Figure A1 in Annexure A). The PCS in wall 3 of RBMS are 0.41 N/mm^2, 0.44 N/mm^2, 0.47 N/mm^2, 0.25 N/mm^2 and 0.27 N/mm^2 for soil profile types SA, SB, SC, SD and SE, respectively. In wall 3 of RBMS, there is a decrement in PCS by 33%, 33%, 35%, 68% and 68% for soil profile types SA, SB, SC, SD and SE, respectively, as compared to that of UBMS. The PCS in wall 3 of UBMS for soil profiles type SB, SC, SD and SE are increased by 8%, 18%, 26% and 38%, respectively, compared to that for soil profile type SA. In wall 3 of RBMS, the PCS are increased by 6% and 7% for soil profile types SB and SC, respectively, as compared to that for soil profile type SA. There is decrement of 33% and 31% in PCS for soil profiles type SD and SE, respectively, in wall 3 of RBMS compared to that for soil profile type SA.

5.2.4 PCS in transverse solid wall

The PCS in transverse solid wall (wall 4) of UBMS are 0.60 N/mm^2, 0.65 N/mm^2, 0.70 N/mm^2, 0.75 N/mm^2 and 0.82 N/mm^2 for soil profile types SA, SB, SC, SD and SE, respectively (refer Figure A2 in Annexure A). The PCS in wall 4 of RBMS are 0.40 N/mm^2, 0.44 N/mm^2, 0.47 N/mm^2, 0.24 N/mm^2 and 0.26 N/mm^2 for soil profile types SA, SB, SC, SD and SE, respectively. In wall 4 of RBMS, there is a decrement in PCS by 33%, 32%, 33%, 68% and 68% for soil profile types SA, SB, SC, SD and SE, respectively, as compared to that of UBMS. The PCS in wall 4 of UBMS for soil profiles type SB, SC, SD and SE is increased by 8%, 17%, 25% and 37%, respectively, compared to that of SA. In wall 4 of RBMS, the PCS are increased by 10% and 18% for soil profile types SB and SC, respectively, as compared to that for SA. There is decrement of 40% and 35% in PCS for soil profile types SD and SE, respectively, in wall 4 of RBMS compared to that of soil profile type SA.

5.2.5 PCS in other walls

The details of PCS in other longitudinal and transverse walls with openings (wall 2a and wall 3a, respectively) are shown in Annexure A (refer Figures A3 and A4), respectively. The similar trend is observed in other walls as explain earlier for wall 1 and 3.

5.2.6 Overall trend in PCS

The PCS are significantly increased in all walls of UBMS for soil profile types from SA to SE. In RBMS, the PCS are also increased in all walls for soil profile types from SA to SC and have increasing trend from SD to SE but with lesser magnitude in comparison to that for soil profile types from SA to SC. The PCS is reduced further in all walls of RBMS for soil profile types SD and SE due to the increased cross-section, concrete strength and steel re-bar of V.S and H.S. Generally, the PCS is reduced by 29% to 68% in RBMS compared to that of UBMS due to the provided RC stiffeners. The PCS in walls with openings are more as compared to that in solid walls. The reason for increased PCS is openings in the wall because the stress concentration is maximum at the corners of openings due to absence of V.S. The similar behaviour in the experimental work is also reported by Vanin and Foraboschi (2012). The six specimens of brick masonry walls with an opening were tested. These walls were subjected to a constant monotonic horizontal force and vertical load that was gradually increased until the kinematic mechanism condition was reached. The stress concentration in all walls is maximum at the corners of the openings which results in the failure or cracking of masonry and kinetic mechanism is considered.

5.3 Maximum top displacement (Δ) in UBMS and RBMS

In this study, the maximum top displacement (in-plane) of UBMS and RBMS is considered for the longitudinal wall with openings (wall 1), longitudinal solid wall (wall 2), transverse wall with opening (wall 3) and transverse solid wall (wall 4).

5.3.1 Δ in transverse walls with openings

The maximum top displacement (Δ) in transverse walls with openings (wall 3) of UBMS and RBMS for soil profile type SD and all seismic zones are shown in Figure 5.3. It is noted that Δ in wall 3 of UBMS and RBMS for seismic zone 1 is 0.77 mm and 0.60 mm, respectively. The Δ in wall 3 of RBMS is decreased by 17% as compared to that of UBMS. The reason for decreased Δ in wall 3 of RBMS is the addition of stiffeners. For seismic zone 2A, the Δ in wall 3 is 1.26 mm and 1.02 mm for UBMS and RBMS, respectively. This is a decrease of 19% for Δ in wall 3 of RBMS compared to that of UBMS. The decrement of Δ in wall 3 of RBMS is due to the provided 115 mm x 115 mm V.S and 230 mm x 75 mm H.S compared to that of UBMS. The Δ for seismic zone 2A in wall 3 is increased by 75% in UBMS and 70% in RBMS as compared to that for seismic zone 1. In wall 3 of UBMS the Δ is 1.55 mm and in RBMS it is 1.10 mm for seismic zone 2B. In wall 3 of RBMS, the Δ is reduced by 29% with respect to that of UBMS. The increments in Δ of wall 3 are 40% and 13% for UBMS and RBMS, respectively, when compared with that for seismic zone 2A. The Δ in wall 3 for seismic zone 2B is increased by 115% and 83% in UBMS and RBMS, respectively, compared to that for seismic zone 1. The Δ is reduced in RBMS because of the reason as explain earlier. For seismic zone 3, the Δ in wall 3 is 1.94 mm for UBMS and 1.30 mm for RBMS. Thus, the Δ in wall 3 of RBMS is decreased by 33% compared to that of UBMS. The Δ in wall 3 is increased for seismic zone 3 by 25% in UBMS and 18% in RBMS compared to that for seismic zone 2B. The increment in Δ is 169% and 117% in wall 3 of UBMS and RBMS, respectively, compared to that for seismic zone 1. The Δ in wall 3 for seismic zone 4 is 2.33 mm and 1.59 mm for UBMS and RBMS, respectively. This Δ is decreased by 31% in wall 3 of RBMS when compared with that of UBMS. For seismic zone 4, the Δ is increased by 52% and 48% in wall 3 of UBMS and RBMS, respectively, compared to that for seismic zone 3. The Δ is increased for seismic zone 4 by 222% in

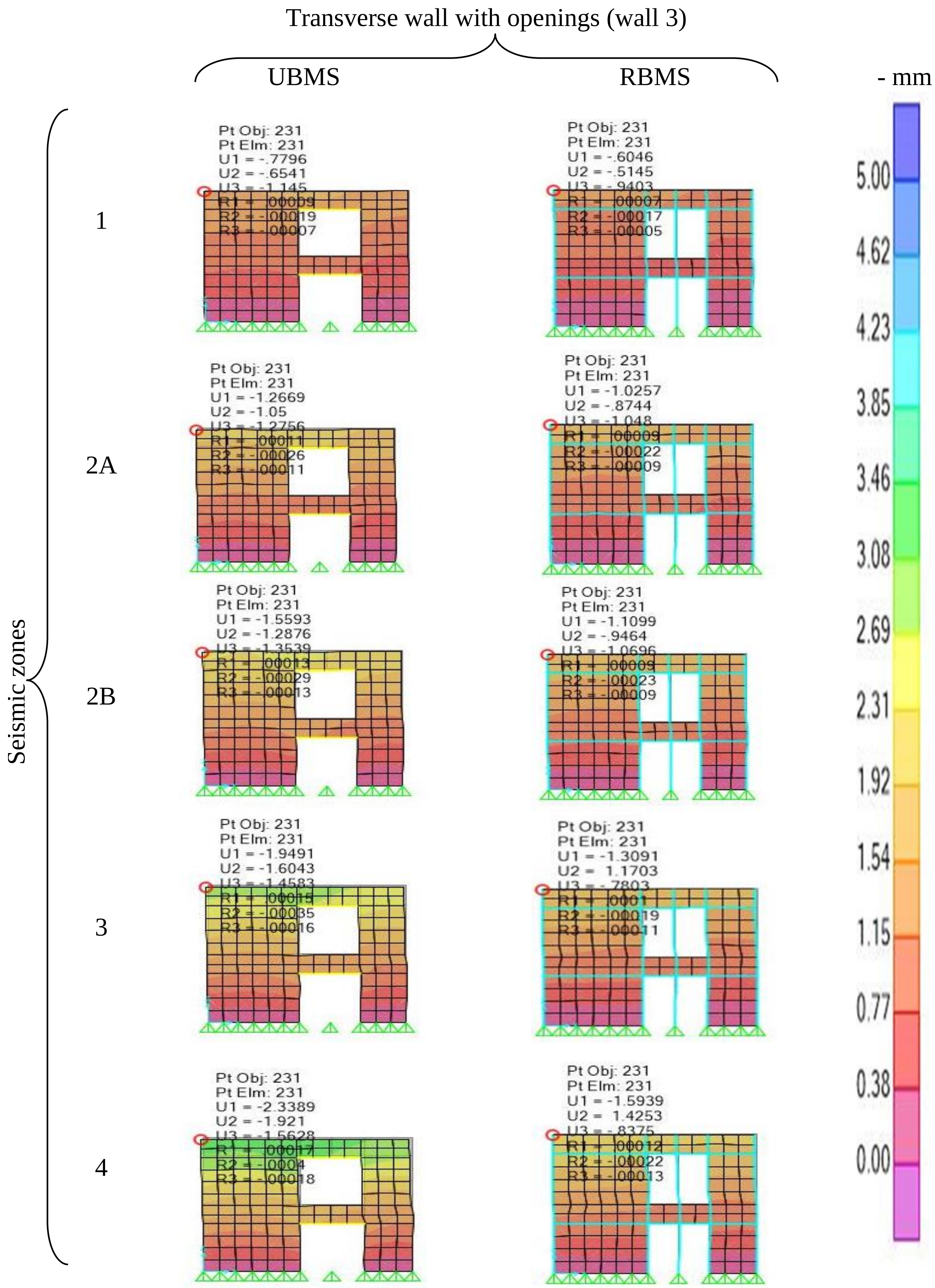


Figure 5.3: Displacements in transverse wall with openings (wall 3) for soil type SD and all seismic zones

UBMS and 165% in RBMS when compared with that for seismic zone 1. As expected, the Δs in wall 3 of UBMS is generally increased with changing seismic zones from 1 to 4. The Δ in wall 3 of RBMS for seismic zone 4 is more when compared with that for seismic zones 1, 2A, 2B and 3 even with larger stiffeners cross-sections (i.e. 230 mm x 230 mm V.S and 230 mm x 150 mm H.S).

5.3.2 Δ in transverse solid wall

As shown in Figure 5.4, the Δ in transverse solid wall (wall 4) of UBMS and RBMS for seismic zone 1 is 0.58 mm and 0.44 mm, respectively. The Δ in wall 4 of RBMS is decreased by 24% as compared to that of UBMS. For seismic zone 2A, the Δ in wall 4 is 0.93 mm and 0.74 mm for UBMS and RBMS, respectively. This is a decrease of 20% for Δ in wall 4 of RBMS compared to that of UBMS. The Δ in wall 4 for seismic zone 2A is increased by 60% in UBMS and 68% in RBMS as compared to that for seismic zone 1. In wall 4 of UBMS, the Δ is 1.14 mm and in RBMS it is 0.80 mm for seismic zone 2B. In wall 4 of RBMS, the Δ are reduced by 30% with respect to that of UBMS. For seismic zone 2B, the increments are 37% and 14% for Δ in wall 4 of UBMS and RBMS, respectively, when compared with that for seismic zone 2A. The Δ in wall 4 for seismic zone 2B is increased by 97% and 82% in UBMS and RBMS, respectively, compared to that for seismic zone 1. For seismic zone 3, the Δ in wall 4 is 1.43 mm for UBMS and 0.90 mm for RBMS. Thus, the Δ in wall 4 of RBMS is decreased by 37% compared to that of UBMS. The Δ in wall 4 is increased for seismic zone 3 by 25% in UBMS and 12% in RBMS compared to that for seismic zone 2B. There is 147% and 105% increment for Δ in wall 4 of UBMS and RBMS, respectively, compared to that for seismic zone 1. The Δ in wall 4 for seismic zone 4 is 1.71 mm and 1.10 mm for UBMS and RBMS, respectively. The Δ in wall 3 of RBMS is decreased by 36% when compared with that of UBMS. For seismic zone 4, the Δ are increased by 48% and 45% in wall 4 of UBMS and RBMS, respectively, compared to that for seismic zone 3. The Δ in wall 4 for seismic zone 4 is increased by 195% in UBMS and 150% in RBMS as compared to that for seismic zone 1.

5.3.3 Δ in longitudinal wall with openings

The Δ in longitudinal wall with openings (wall 1) of UBMS are 1.79 mm, 2.76 mm, 3.34 mm, 4.12 mm and 4.90 mm for seismic zones 1, 2A, 2B, 3 and 4, respectively (refer Figure B1 in Annexure B). In wall 1 of RBMS, the Δ are 1.42 mm, 2.27 mm, 2.44 mm, 2.85 mm and 3.44 mm for seismic zones 1, 2A, 2B, 3 and 4, respectively. The Δ in wall 1 of RBMS are reduced by 21%, 18%, 27%, 31% and 30% for seismic zones 1, 2A, 2B, 3 and 4, respectively, as compared to that of UBMS. In wall 1 of UBMS, the Δ for seismic zones 2A, 2B, 3 and 4 are increased by 54%, 90%,134% and 178%, respectively, when compared to that for seismic zone 1. The Δ in wall 1 of RBMS are increased by 60%, 72%, 101% and 142% for seismic zones 2A, 2B, 3 and 4, respectively, compared to that for seismic zone 1.

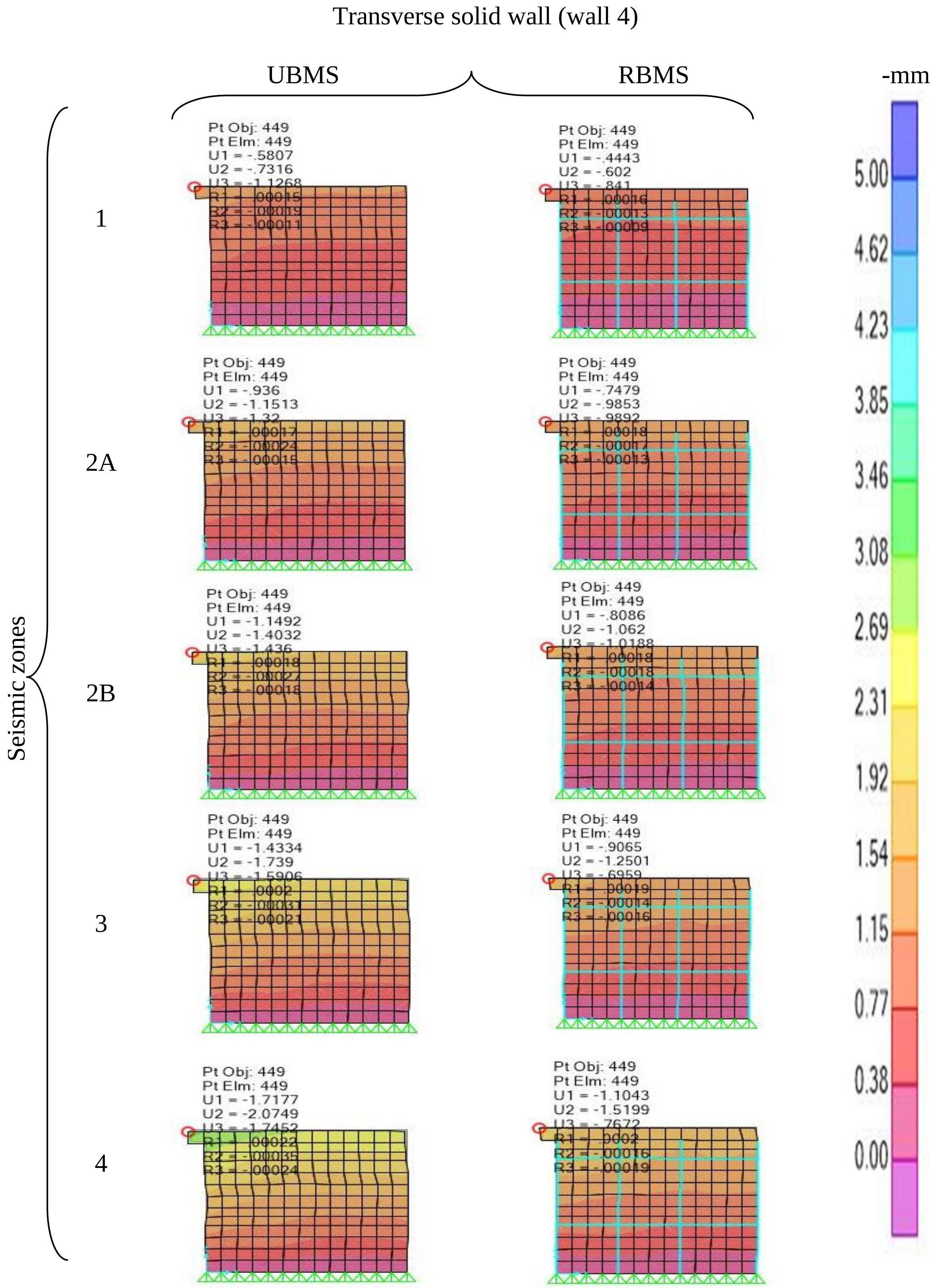


Figure 5.4: Displacements in transverse solid wall (wall 4) for soil profile type SD and all seismic zones

5.3.4 Δ in longitudinal solid wall

The Δ in longitudinal solid wall (wall 2) of UBMS are 1.80 mm, 2.67 mm, 3.19 mm, 3.89 mm and 4.51 mm for seismic zones 1, 2A, 2B, 3 and 4, respectively (refer Figure B2 in Annexure B). In wall 2, the Δ of RBMS are 1.36 mm, 2.12 mm, 2.27 mm, 2.55 mm and 3.07 mm for seismic zones 1, 2A, 2B, 3 and 4, respectively. The Δ in wall 2 of RBMS are decreased by 24%, 21%, 29%, 34% and 32% for seismic zones 1, 2A, 2B, 3 and 4, respectively, as compared to that of UBMS. The Δ in wall 2 for seismic zones 2A, 2B, 3 and 4 in UBMS are increased by 48%, 77%, 116% and 151%, respectively, when compared with that for seismic zone 1. In RBMS, the Δ in wall 2 are increased by 56%, 67%, 88% and 126% for seismic zones 2A, 2B, 3 and 4, respectively, compared to that for seismic zone 1.

5.3.5 Δ in other walls

The details of other longitudinal and transverse walls (wall 2a and wall 3a, respectively) are shown in Annexure B (refer Figures B3 and B4). The similar trend is observed in other walls as explain earlier for wall 1 and 3.

5.3.6 Overall trend in Δ

The Δ has increasing trend with relatively steep slope in all walls of UBMS from seismic zones 1 to 4. Similarly, in RBMS, the Δ in all walls has also growing trend from seismic zones 1 to 4 but with moderate slope. As expected, the Δs are less in RBMS compared to that of UBMS due to the addition of stiffeners. The Δ in RBMS is increased from seismic zones 1 to 4 even with increased cross-section, concrete strength and steel re-bar of V.S and H.S. According to UBC 97, the peak ground acceleration range increases from seismic zones 1 to 4, hence the Δ is increased both in UBMS and RBMS. The Δ in solid walls is less as compared to that in walls with openings. The reason for decreased Δ is higher stiffness of solid walls as compared to that of walls with openings.

5.4 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-modeling of brick masonry. For this current study, the shear stress is considered and the limits of crack prediction 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 i.e. wall 1 (viewed from the inside) for seismic zone 2B and all soil profile types is shown in Figure 5.5. It may be noted that the cracks appeared at the left corners of windows and at the base in wall 1 of ground and first floor of UBMS for soil profile type SA. The length and number of cracks in wall 1 of RBMS for soil profile type SA are less as compared to that of UBMS. The reason for decreased length and number of cracks in RBMS are the provided V.S and H.S, enhancing the stiffness of the structure. In UBMS and RBMS, the length and number of the cracks in the wall 1 increases at the corner of windows and at the base of wall 1 when shifting from soil profile type SA (hard rock) to SB (rock). The length and number of cracks in wall 1 of RBMS are less compared to that of UBMS for soil profile type SB. In soil profile type SC (dense soil and soft rock), the number and length of cracks are further increased for both UBMS and RBMS. The length and number of cracks are also less in RBMS as compared to that of UBMS for soil profile type SC. The number of the crack increases and most of cracks meet together at the corner of window and base of the wall 1 for soil profile type SD (stiff soil) in UBMS. The cracks are considerably less in wall 1 of RBMS compared to that of UBMS for soil profile type SD. It may be noted that these cracks are less in comparison to that of RBMS for soil profile type SC. The reason for reduction of cracks in wall 1 of RBMS for soil profile type SD is the large cross-section of V.S (i.e. 230 mm x 230 mm) and H.S (i.e. 230 mm x 150 mm). There is severe cracking in wall 1 of UBMS for soil profile type SE (soft soil) as shown in bottom left sketch of Figure 8. Few cracks are appeared in wall 1 of RBMS for soil profile type SE. These cracks are a little more in comparison to that for soil profile type SD. It may be noted that only steel reinforcement is increased in V.S and H.S for soil profile type SE in comparison to that for soil profile type SD. The cracks in wall 1 of UBMS are increased significantly for soil profile types from SA to SE. Similarly, in RBMS having 115 mm x 115 mm V.S and 230 mm x 75 mm H.S, the cracks lengths are also increased for soil profile types from SA to SC.

The length of crack in RBMS is less as compared to that of UBMS for soil profile types SA, SB and SC. Even with 230 mm x 230 mm vertical stiffener and 230 mm x 150 mm horizontal stiffener in RBMS, the cracks are appeared but with smaller lengths for soil profile types SD and SE. The cracks of smaller length are produced at the corners of window openings due to the stress concentration because of absence of V.S. The crack due to stress concentration at the openings is also reported by Shahzada et al. (2012) in experimental seismic performance evaluation of

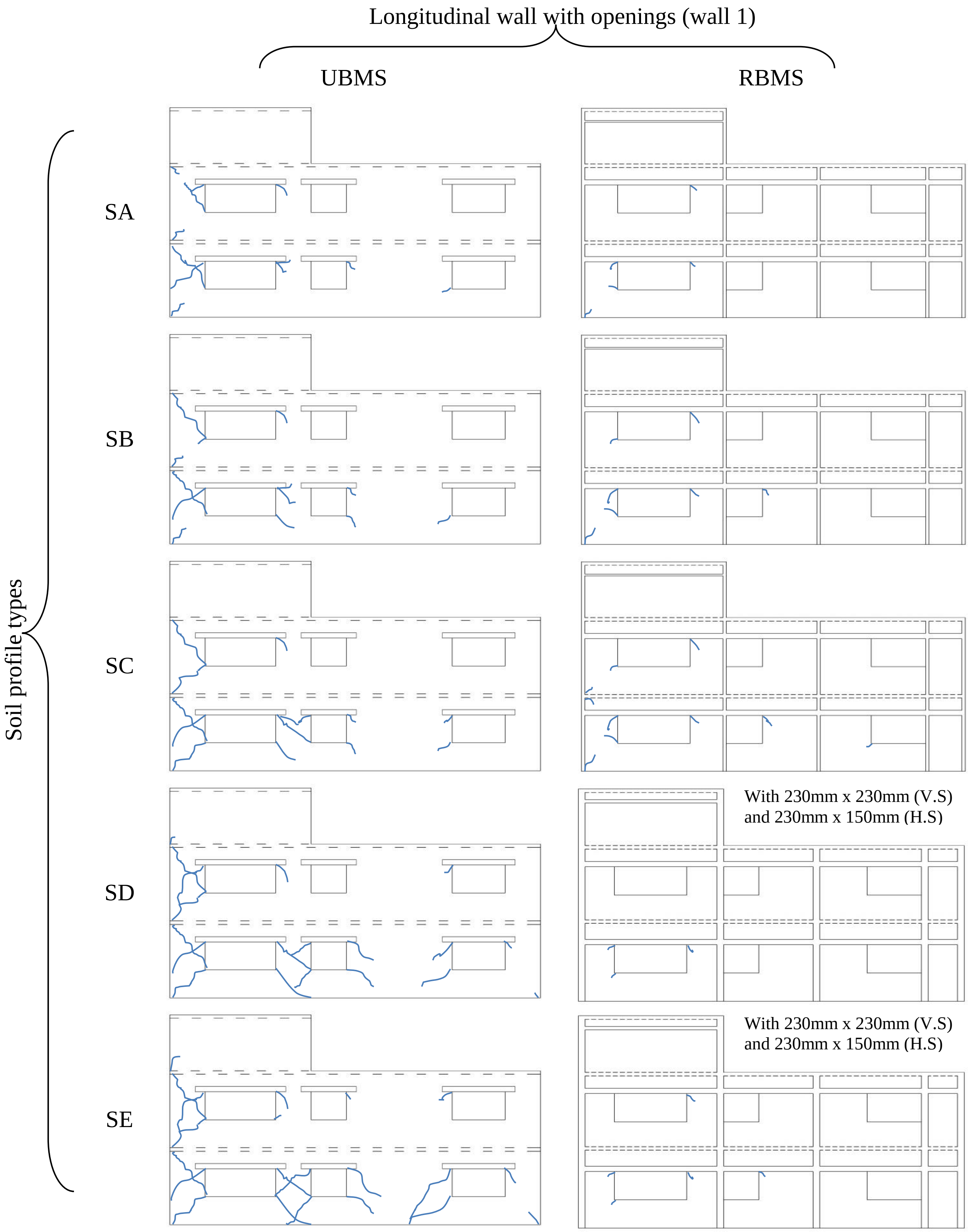


Figure 5.5: Prediction of crack propagation in longitudinal wall with openings i.e. wall 1 (viewed from inside) for seismic zone 2B and all soil profile types

unreinforced brick masonry buildings. The diagonal cracks are appeared approximately at an angle of 45 degree and this pattern for brick masonry is also reported in literature by Vanin and Foraboschi (2012). The diagonal pattern shows that the cracks are initiated between the joints of the brick masonry. Similar crack patterns were observed in UBMS during the 2005 Kashmir earthquake (Naseer *et al.* 2010, Shahzada *et al.* 2012). The appearance of cracks in the wall shows that the plastic hinges are formed at the corner and the wall behaves like a column due to the large opening. The diagonal cracks are observed because of the soften behaviour (joint between brick and mortar) of brick masonry wall. The shear fracture (diagonal cracks) occurs in the wall because the PCS reaches the diagonal tension strength of the masonry wall.

5.5 Comparison of principle critical stress in UBMS and RBMS

The summary of PCS for seismic zone 2B and all soil profile types are shown in Figure 5.6. It may be noted that PCS of RBMS are compared to that of UBMS. The PCS in longitudinal wall with openings (wall 1) of RBMS are decreased by 0.49 MPa, 0.53 MPa, 0.51 MPa, 1.05 MPa and 1.05 MPa for soil profile types SA, SB, SC, SD and SE, respectively. The PCS in longitudinal solid wall (wall 2) of RBMS are reduced by 0.23 MPa, 0.24 MPa, 0.22MPa, 0.52 MPa and 0.55 MPa for soil profile types SA, SB, SC, SD and SE, respectively. There is a decrement in PCS of transverse wall with opening (wall 3) by 0.20 MPa, 0.22 MPa, 0.25 MPa, 0.52 MPa and 0.57 MPa for soil profile types SA, SB, SC, SD and SE, respectively, in RBMS. The PCS in transverse solid wall (wall 4) are reduced by 0.20 MPa, 0.21 MPa, 0.23 MPa, 0.51 MPa and 0.56 MPa for soil profile types SA, SB, SC, SD and SE, respectively, in RBMS. The PCS are reduced up to 57% and 68% in longitudinal and transverse walls with openings of RBMS, respectively, compared to that of UBMS. The PCS are decreased up to 62% and 68% in longitudinal and transverse solid walls, respectively, in RBMS, compared to that of UBMS. The rate of increment for PCS in wall 1, wall 2, wall 3 and wall 4 of UBMS for soil profile types from SA to SC are 4.9%, 4.5%, 5.7% and 5.4%, respectively. The rate of increment for PCS in wall 1, wall 2, wall 3 and wall 4 of RBMS for soil profile types from SA to SE are 5%, 4%, 3% and 3.5%, respectively. These increments are 2% for all walls when soil profile type is changed from SD to SE. The rate of increment in RBMS for soil profile types from SA to SC is more as compared to that from SD to SE because of larger cross-section of stiffeners in later cases. The PCS is increased linearly in UBMS while in RBMS it is linear up to some extent.

The details of PCS in UBMS and RBMS for seismic zone 1, 2A, 3 and 4 and all soil profile types are shown in Annexure C (refer Figure C1).

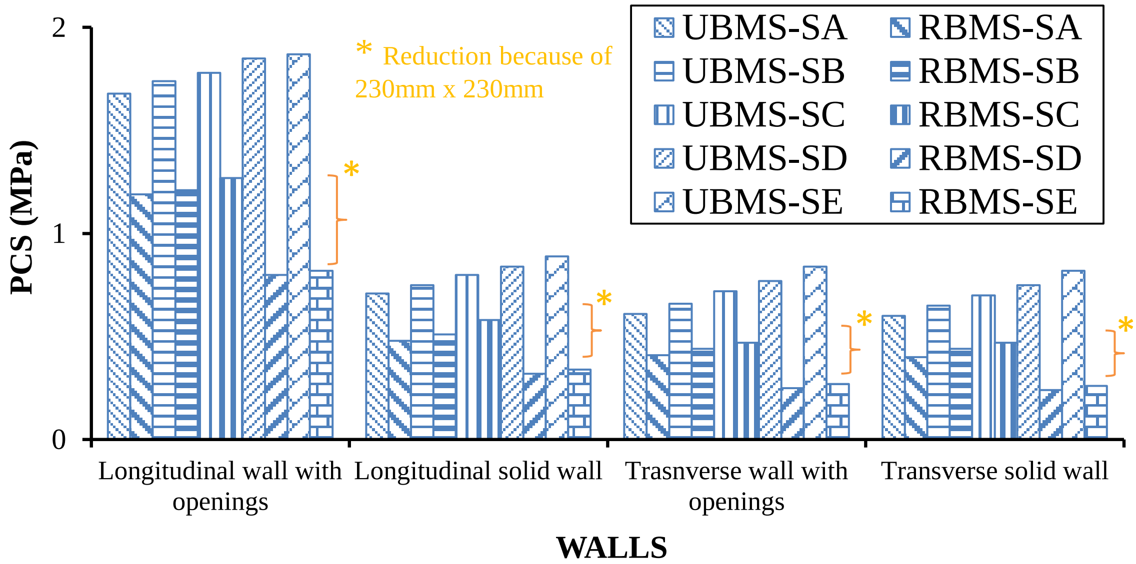


Figure 5.6: Summary of PCS for seismic zone 2B and all soil profile types

5.6 Comparison of maximum top displacement in UBMS and RBMS

The summary of Δ for soil profile type SD and all seismic zones is shown in Figure 5.7. The comparison of Δ is made for UBMS and RBMS. The Δ in longitudinal wall with openings in RBMS is reduced by 0.37 mm, 0.49 mm, 1.08 mm, 1.27 mm and 1.46 mm for seismic zones 1, 2A, 2B, 3 and 4, respectively. The Δ in longitudinal solid wall of RBMS is decreased by 0.44 mm, 0.55 mm, 1.16 mm, 1.34 mm and 1.44 mm for seismic zones 1, 2A, 2B, 3 and 4, respectively. The Δ of transverse wall with openings in RBMS is decreased by 0.12 mm, 0.24 mm, 0.53 mm, 0.64 mm and 0.73 mm for seismic zones 1, 2A, 2B, 3 and 4, respectively. The Δ of transverse solid wall in RBMS is reduced by 0.14 mm, 0.19 mm, 0.44 mm, 0.53 mm and 0.61 mm for seismic zones 1, 2A, 2B, 3 and 4, respectively. There is decrement in Δ of longitudinal and transverse walls with openings up to 31% and 33%, respectively in RBMS. The Δ in longitudinal and transverse solid walls is decreased up to 32% and 37%, respectively, for RBMS.

The rate of increment in Δ of wall 1, wall 2, wall 3 and wall 4 for UBMS are 75%, 66%, 38% and 27%, respectively. In RBMS, the rate of increment in Δ of wall 1, wall 2, wall 3 and wall 4 are 46%, 38%, 22% and 14%, respectively. The Δ is increased linearly in both UBMS and RBMS, but the rate of increment is more in UBMS compared to that in RBMS.

The details of Δ in UBMS and RBMS for soil profile types SA, SB, SC and

SC and all seismic zones are shown in Annexure D (refer Figure D 1).

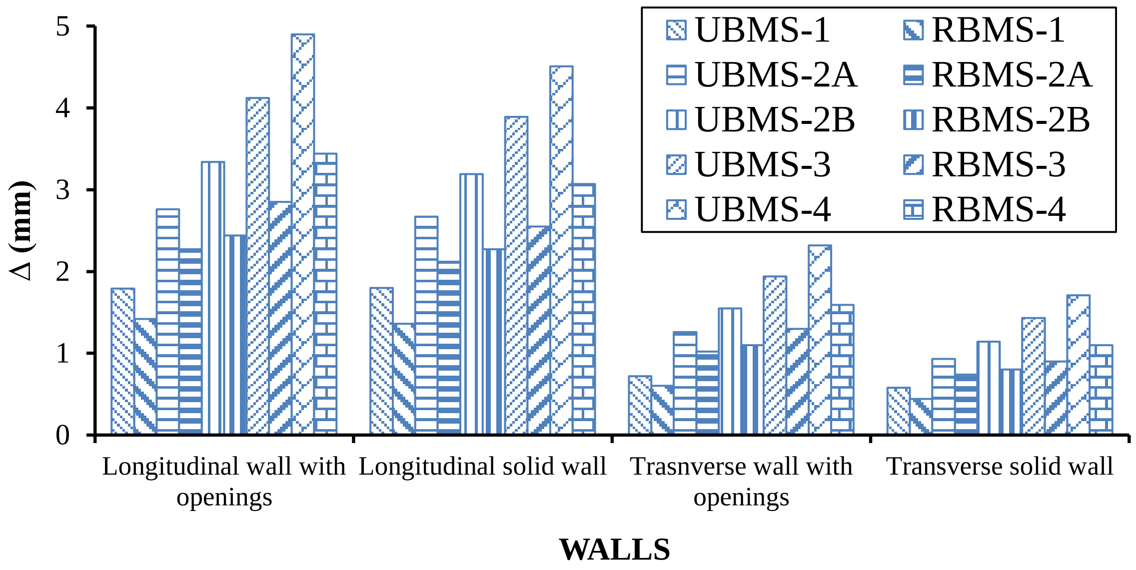


Figure 5.7: Summary of maximum top displacement for soil profile type SD and all seismic zones

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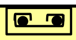
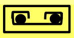
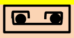
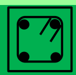
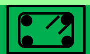
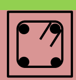
5.7 Validation of diagonal approach for design of RC vertical and horizontal stiffeners in RBMS

The range of base shear (V), principle critical stress and maximum top displacement (in-plane) are set for confirming proposed diagonal approach for specific cross-sections of RC vertical and horizontal stiffeners as shown in Table 5.1. The results of V, PCS and Δ are considered for all soil profile types and all seismic zones, making a matrix of 5 x 5 i.e. 25 cases. For these 25 cases, a total of nine combinations of seismic parameters based on proposed diagonal approach are considered. The range values at Sr. No. 1 and 9, 2 and 8, 3 and 7, 4 and 6, and 5 in Table 5.1 represent the results of one, two, three, four and five combinations, respectively, of seismic parameters (soil profile type and seismic zone). Accordingly, nine combinations of RC vertical and horizontal stiffeners are proposed.

For combination of soil profile type SA and seismic zone 1, the value of V, PCS and Δ in UBMS are 93 kN, 1.45 MPa and 1.2 mm, respectively. With the proposed cross-sections (shown in Sr. No.1 of Table 5.1), the V, PCS and Δ in RBMS are 98 kN, 1.10 MPa and 0.9 mm, respectively. It may be noted that the base shear is increased in RBMS due to the difference in densities of reinforced concrete and brick masonry. For the combination of (i) soil profile type SA and seismic zone 2A and (ii) soil profile type SB and seismic zone 1, the range of V, PCS and Δ in UBMS are 124-186 kN, 1.55-1.65 MPa and 1.9-2.3 mm, respectively. These values in RBMS are

129-191 kN, 1.05-1.15 MPa and 1.1-1.4 mm, respectively (obtained with the provision of V.S and H.S mentioned at Sr. No.2 in Table 5.1). The range of V, PCS and Δ in UBMS are 142-247 kN, 1.6-1.7 MPa and 2.1-3.0 mm, respectively, for the combination of (i) soil profile type SA and seismic zone 2B (ii) soil profile type SB and seismic zone 2A and (iii) soil profile type SC and seismic zone 1. In RBMS, these ranges are 144-256 kN, 1.1-1.2 MPa and 1.2-1.8 mm, respectively, with proposed combination of cross-sections of V.S and H.S (given in Sr. No.3 of Table 5.1). The ranges of V, PCS and Δ for combinations of (i) soil profile type SA and seismic zone 3 (ii) soil profile type SB and seismic zone 2B (iii) soil profile type SC and seismic zone 2A and (iv) soil profile type SD and seismic zone 1 are 186-376 kN, 1.65-1.75 MPa and 1.8-3.0 mm, respectively, in UBMS. For these combinations, the V, PCS and Δ ranges with proposed combination of V.S and H.S (presented in Sr. No.4 of Table 5.1) are 191-365 kN, 1.15-1.25 MPa and 1.4-2.4 mm, respectively, in RBMS. For combinations of (i) soil profile type SA and seismic zone 4 (ii) soil profile type SB and seismic zone 3 (iii) soil profile type SC and seismic zone 2B (iv) soil profile type SD and seismic zone 2A and (v) soil profile type SE and seismic zone 1, the ranges of V, PCS and Δ in UBMS are 298-503 kN, 1.7-1.8 MPa and 2.5-3.7 mm, respectively. These ranges in RBMS are 303-512 kN, 1.2-1.3 MPa and 2.0-3.1 mm, respectively, with proposed cross-sections of V.S and H.S (at Sr. No.5 of Table 5.1). The range of V, PCS and Δ in UBMS for combination of (i) soil profile type SB and seismic zone 4 (ii) soil profile type SC and seismic zone 3 (iii) soil profile type SD and seismic zone 2B (iv) soil profile type SE and seismic zone 2A are 471-627 kN, 1.75-1.85 MPa and 3.4-4.3 mm, respectively. The ranges in RBMS for proposed cross-sections of V.S and H.S (shown in Sr. No.6 of Table 5) are 472-672 kN, 0.8-0.9 MPa and 2.3-3.2 mm for V, PCS and Δ, respectively. It may be noted that the further reduction in PCS of RBMS is because of larger cross-sections of stiffeners i.e. 230 mm x 230 mm V.S and 230 mm x 150 mm H.S. In UBMS, the ranges of V, PCS and Δ for combinations (i) soil profile type SC and seismic zone 4 (ii) soil profile type SD and seismic zone 3 and (iii) soil profile type SE and seismic zone 2B are 533-658 kN, 1.80-1.90 MPa and 3.9-4.7 mm, respectively. In RBMS, these ranges for V, PCS andΔ are 573-707 kN, 0.85-0.95 MPa and 2.7-3.3 mm, respectively, with proposed combinations of V.S and H.S (given in Sr. No.7 of Table 5.1). For combinations of (i) soil profile type SD and seismic zone 4 and (ii) soil profile type SE and seismic zone 3, the ranges are 565-689 kN, 1.85-1.95 MPa and 4.1-4.9 mm for V, PCS and Δ,

Table 5.1: Range of base shear, principle critical stress and maximum top displacement for defining diagonal approach

Sr. No.	Cross-section of vertical stiffeners	Cross-section of horizontal stiffeners	fc' (MPa)	Without stiffeners: Base shear (kN)	Without stiffeners: Principle critical stresses (MPa)	Without stiffeners: Maximum top displacements (mm)	With stiffeners: Base shear** (kN)	With stiffeners: Principle critical stresses (MPa)	With stiffeners: Maximum top displacements (mm)
1	 115mm x 115mm with 1-ϕ6	 230mm x 75mm with re-bars 2-ϕ6 and stirrups ϕ6 - 200mm	15	93	1.45	1.2	98	1.10	0.9
2	 115mm x 115mm with 1-ϕ10	 230mm x 75mm with re-bars 2-ϕ10 and stirrups ϕ6 - 150mm	15	124-186	1.55-1.65	1.9-2.3	129-191	1.05-1.15	1.1-1.4
3	 115mm x 115mm with 1-ϕ13	 230mm x 75mm with re-bars 2-ϕ13 and stirrups ϕ6 - 100mm	15	142-247	1.6-1.7	2.1-3.0	144-256	1.1-1.2	1.2-1.8
4	 115mm x 115mm with 1-#10	 230mm x 75mm with re-bars 2-#10 and stirrups ϕ10 - 200mm	15	186-376	1.65-1.75	1.8-3.0	191-365	1.15-1.25	1.4-2.4
5	 115mm x 115mm with 1-#13	 230mm x 75mm with re-bars 2-#13 and stirrups ϕ10 - 150mm	15	298-503	1.7-1.8	2.5-3.7	303-512	1.2-1.3	2.0-3.1
6	 230mm x 230mm with re-bars 4-ϕ6 and ties ϕ6 - 115mm/230mm	 230mm x 150mm with re-bars 4-ϕ6 and stirrups ϕ6 - 200mm	20	471-627	1.75-1.85	3.4-4.3	472-672	0.8-0.9*	2.3-3.2
7	 230mm x 230mm with re-bars 4-ϕ10 and ties ϕ6 - 100mm/200mm	 230mm x 150mm with re-bars 4-ϕ10 and stirrups ϕ6 - 150mm	20	533-658	1.80-1.90	3.9-4.7	573-707	0.85-0.95*	2.7-3.3
8	 230mm x 230mm with re-bars 4-ϕ13 and ties ϕ6 - 90mm/180mm	 230mm x 150mm with re-bars 4-ϕ13 and stirrups ϕ6 - 100mm	20	565-689	1.85-1.95	4.1-4.9	605-743	0.9-1.0*	2.9-3.4
9	 230mm x 230mm with re-bars 4-#10 and ties ϕ10 - 115mm/230mm	 230mm x 150mm with re-bars 4-#10 and stirrups ϕ10 - 200mm	20	845	2.1	5.8	907	1.1*	4.2

Note: * Reduction because of 230mm x 230mm vertical stiffeners and 230mm x 150mm horizontal stiffeners

** Base shear is increased because of stiffeners seismic weight.

respectively. With proposed combinations of V.S and H.S (presented in Sr. No.8 of Table 5.1) in RBMS, the ranges of V, PCS and Δ are 605-743 kN, 0.9-1.0 MPa and 2.9-3.4 mm, respectively. The ranges of V, PCS and Δ in UBMS for combination of soil profile type SE and seismic zone 4 are 845 kN, 2.1 MPa and 5.8mm, respectively. In RBMS, these values are 907 kN, 1.1 MPa and 4.2 mm, respectively, with the proposed combination of cross- sections of V.S and H.S (shown in Sr. No.9 of Table 5.1). The cross-sections of V.S and H.S are 115 mm x 115 mm and 230 mm x 75 mm, respectively, from Sr. No.1 to Sr. No.5. It may be noted that the fc' is 15 MPa and only steel reinforcement is improved in these cross-sections. At Sr. No.6 to Sr. No.9 the cross-sections of V.S and H.S are larger i.e. 230 mm x 230 mm and 230 mm x 150 mm, respectively. It may also be noted that the fc' is increased to 20 MPa for these cross-sections and steel reinforcement is also improved. Hence, all proposed combinations of V.S and H.S in diagonal approach are capable of satisfying the required seismic demands for the respective combinations of seismic parameters (soil profile types and seismic zones) with I = 1 and T $\leq$ 0.7 sec.

5.8 Summary

The ranges of principle critical stress, maximum top displacement against the ranges of base shear without and with proposed RC stiffeners define the diagonal approach. Thus, based on these results, the proposed stiffeners with concept of diagonal approach can be used safely and economically for design of brick masonry structures against seismic loading.

CHAPTER 6

CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

The overall purpose of the research program is to provide safe and economical earthquake-resistant housing technique to public. Therefore, the concept of design optimization of reinforced concrete (RC) vertical and horizontal stiffeners in brick masonry structures is important. In this current study, the design optimization is numerically validated. A simple house to be constructed using brick masonry is considered. The priority for location of stiffeners is usually set in sequence of "at corner", "at junction", "around doors" and finally "around windows". Following this priority, vertical stiffeners around openings of windows in selected house are removed to optimize the number of stiffeners as well. The stiffeners are removed intentionally due to two reasons: (i) the stiffeners are closer to each other and (ii) to make the brick masonry structure economical. By providing maximum number of stiffeners, the structure may become over safe and the design may be uneconomical. A three dimensional geometrical model of the considered brick masonry structure is developed in SAP2000 using macro modelling technique. The principle critical stress (PCS) and maximum top displacement (Δ) are compared for unreinforced brick masonry structures (UBMS) and reinforced brick masonry structures (RBMS). Following conclusions are made:

- Seismic performance of RBMS is better than UBMS, as expected. The length and number of cracks in RBMS are less compared to that of UBMS for all soil profile types and seismic zones.
- The PCS in longitudinal and transverse walls with openings of RBMS are reduced up to 57% and 68%, respectively, as compared to that of UBMS.
- The PCS are decreased up to 62% and 68% in longitudinal and transverse solid walls, respectively, of RBMS compared to that of UBMS.
- In RBMS, the PCS of both walls (i.e. wall with openings and solid wall) is reduced up to 68% compared to that of UBMS.
- There is decrement in Δ of both longitudinal and transverse walls with openings of RBMS up to 31% and 33%, respectively, compared to that of UBMS.

- Compared to the analysis of UBMS, the Δ is decreased up to 32% and 37% in longitudinal and transverse solid walls, respectively, of RBMS.
- In RBMS, the Δ of wall with openings and solid wall is reduced up to 33% and 37%, respectively, compared to that of UBMS.

These results show that the design of RC horizontal and vertical stiffeners based on proposed diagonal approach is safe and economical for particular combination of seismic parameters. Thus, the engineers can safely use the diagonal approach for design of brick masonry structures against seismic loadings. The same concept can also be extended to block masonry houses with little modifications in the size of stiffeners.

6.2 Recommendations

Future recommended topics are:

i. Comparative study of seismic performance of UBMS and RBMS having stiffeners proposed for different seismic parameters (refer Figure F2 for I = 1 and T > 0.7s, F3 for I = 1.25 and T > 0.7s, F4 for I = 1, T $\leq$ 0.7s and near source factor > 1, F5 for I = 1 and T > 0.7s and near source factor > 1 and F6 for I = 1.25, T $\geq$ 0.7s and near source factor > 1 in Annexure F).

ii. Comparison of above results with performance of UBMS and RBMS evaluated by dynamic analysis.

iii. Experimental behaviour of UBMS and RBMS with proposed stiffeners in diagonal approach.

iv. Cost analysis of UBMS and RBMS.

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ANNEXURE A

Principle critical stress for other walls in UBMS and RBMS:

Annexure A1

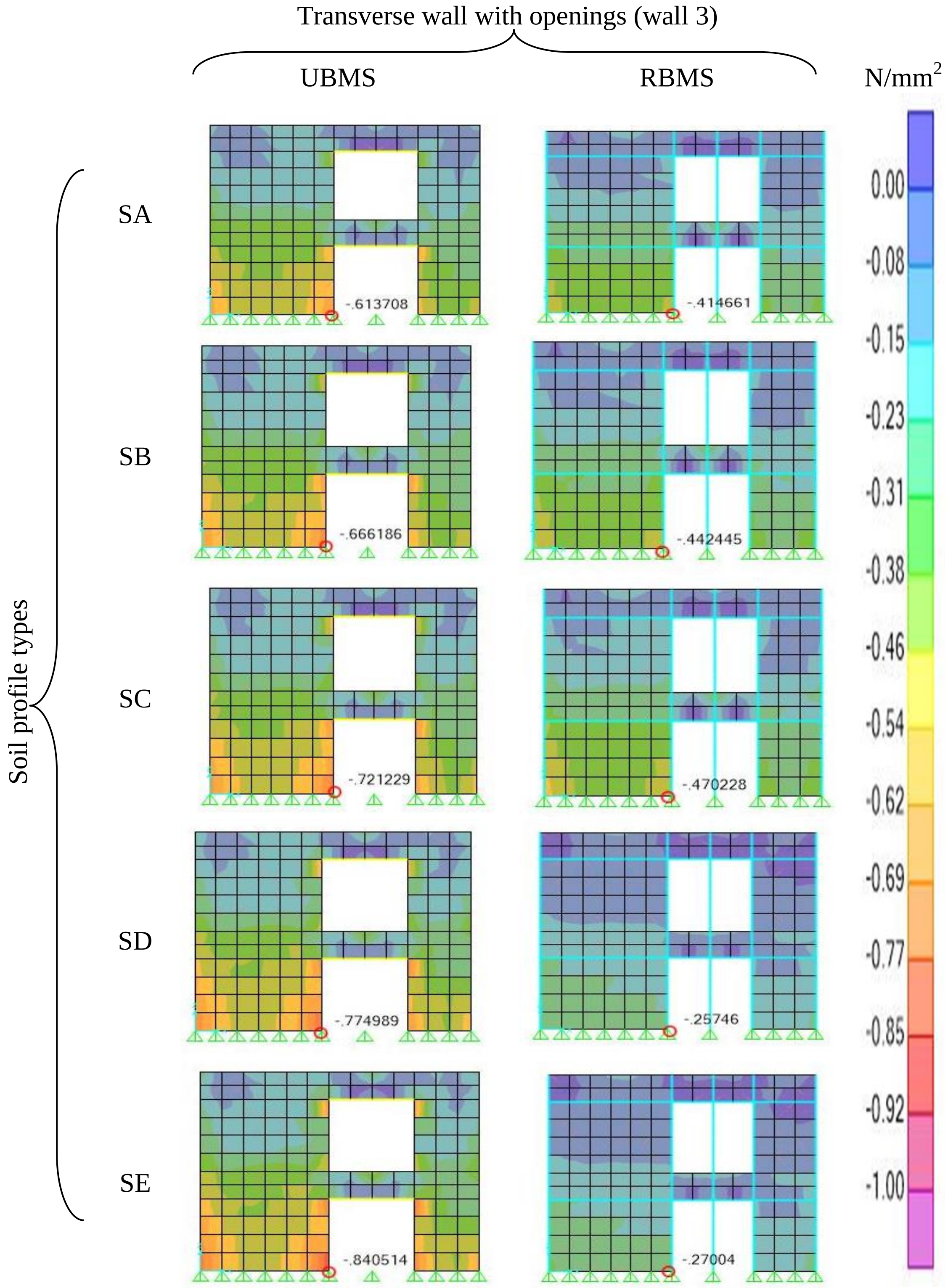


Figure A1: Principle critical stress in transverse wall with openings (wall 3) for seismic zone 2B and all soil profile types

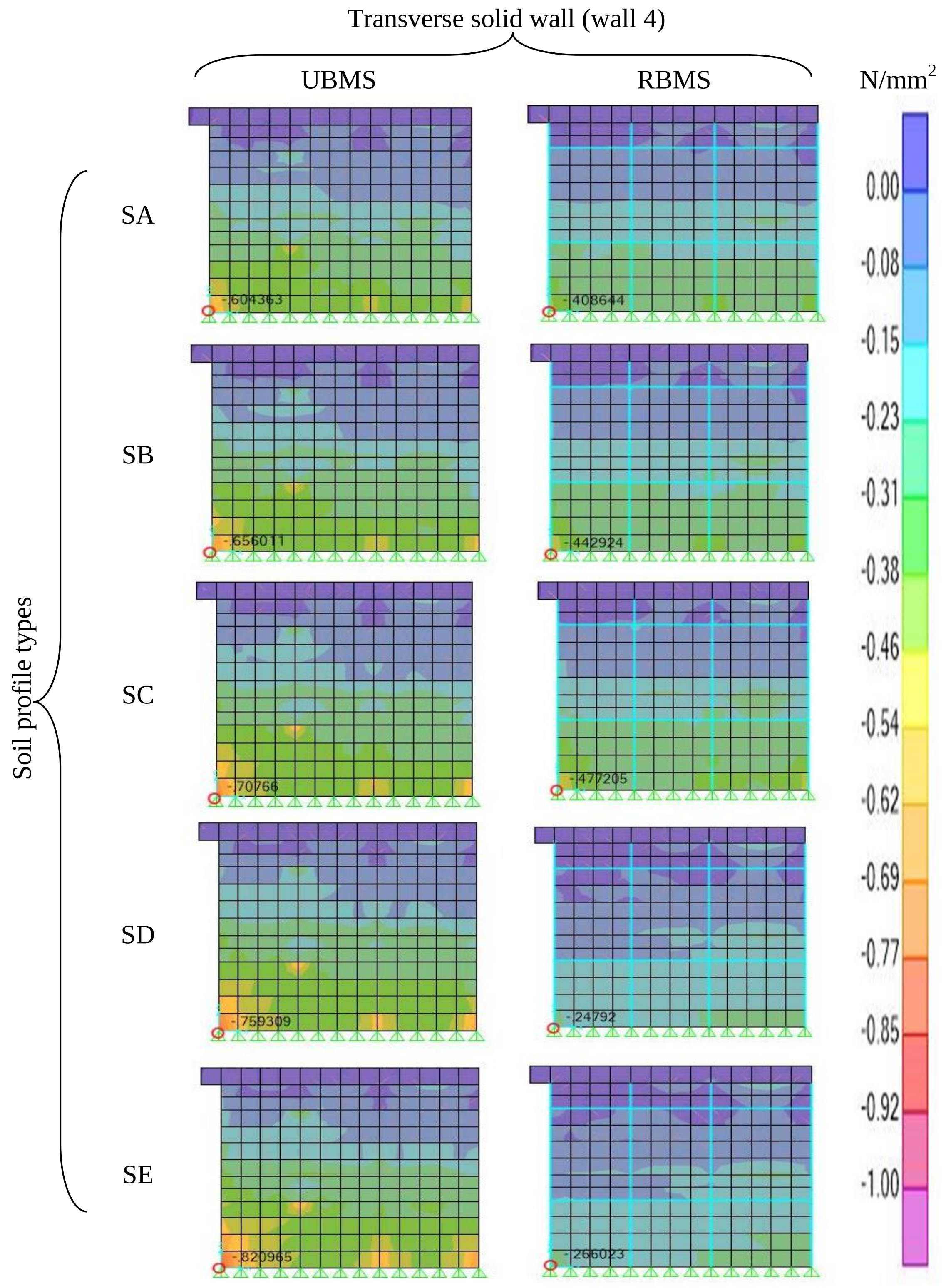


Figure A2: Principle critical stress in transverse solid wall (wall 4) for seismic zone 2B and all soil profile types

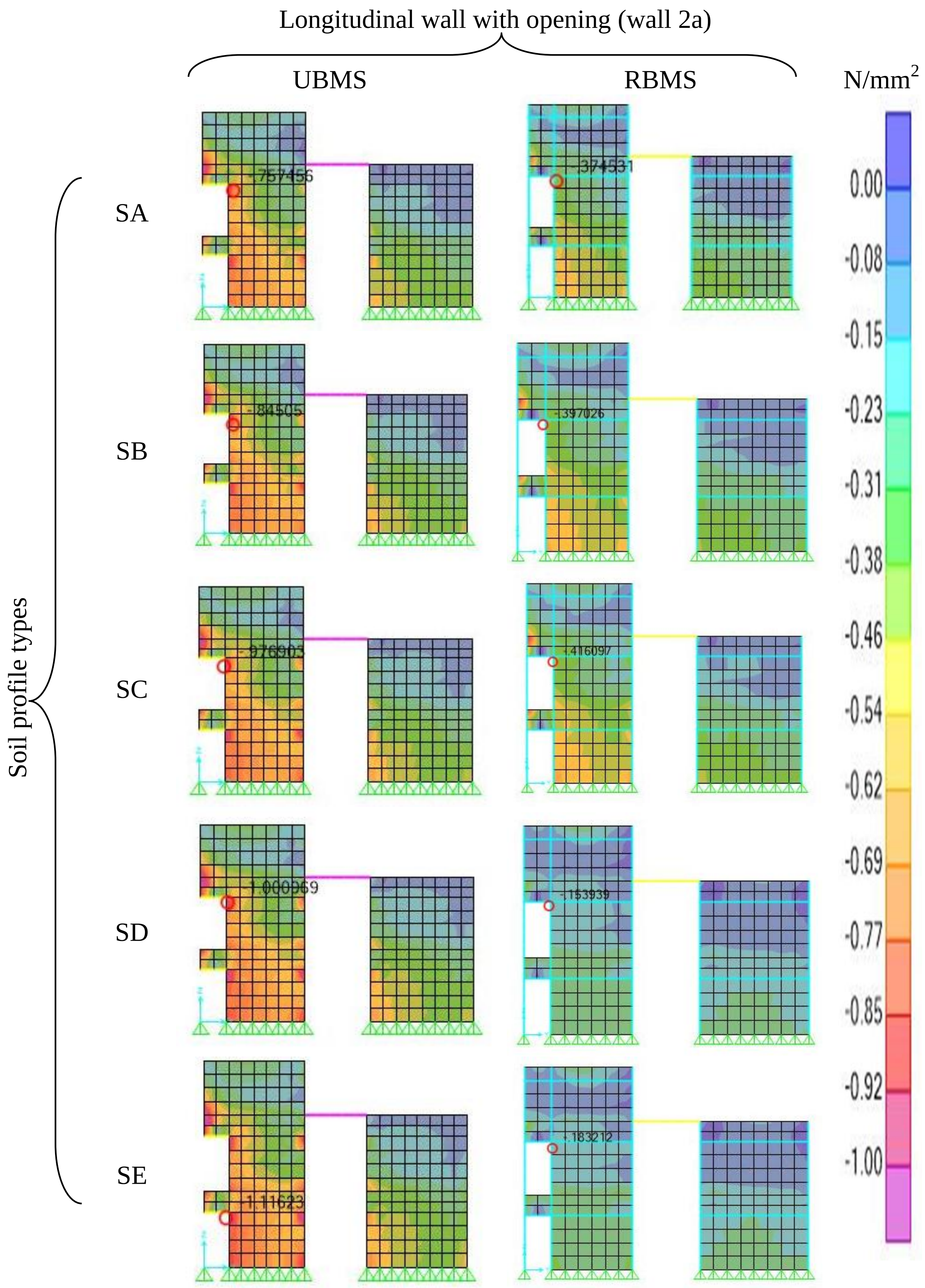


Figure A3: Principle critical stress in longitudinal wall with openings (wall 2a) for seismic zone 2B and all soil profile types

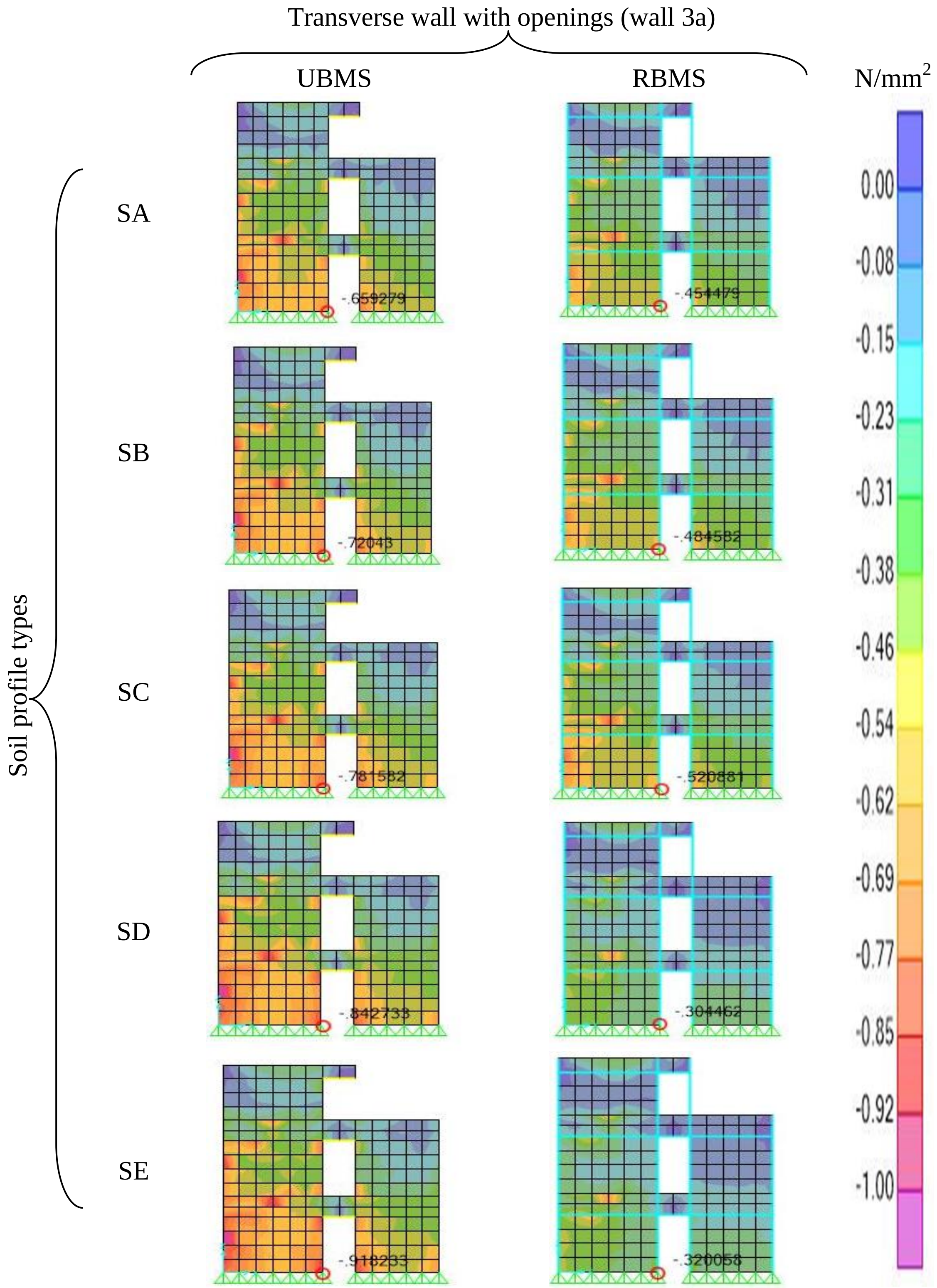


Figure A4: Principle critical stresses in transverse wall with openings (wall 3a) for seismic zone 2B and all soil profile types

ANNEXURE B

Maximum top displacement for other wall in UBMS and RBMS:

Annexure B1

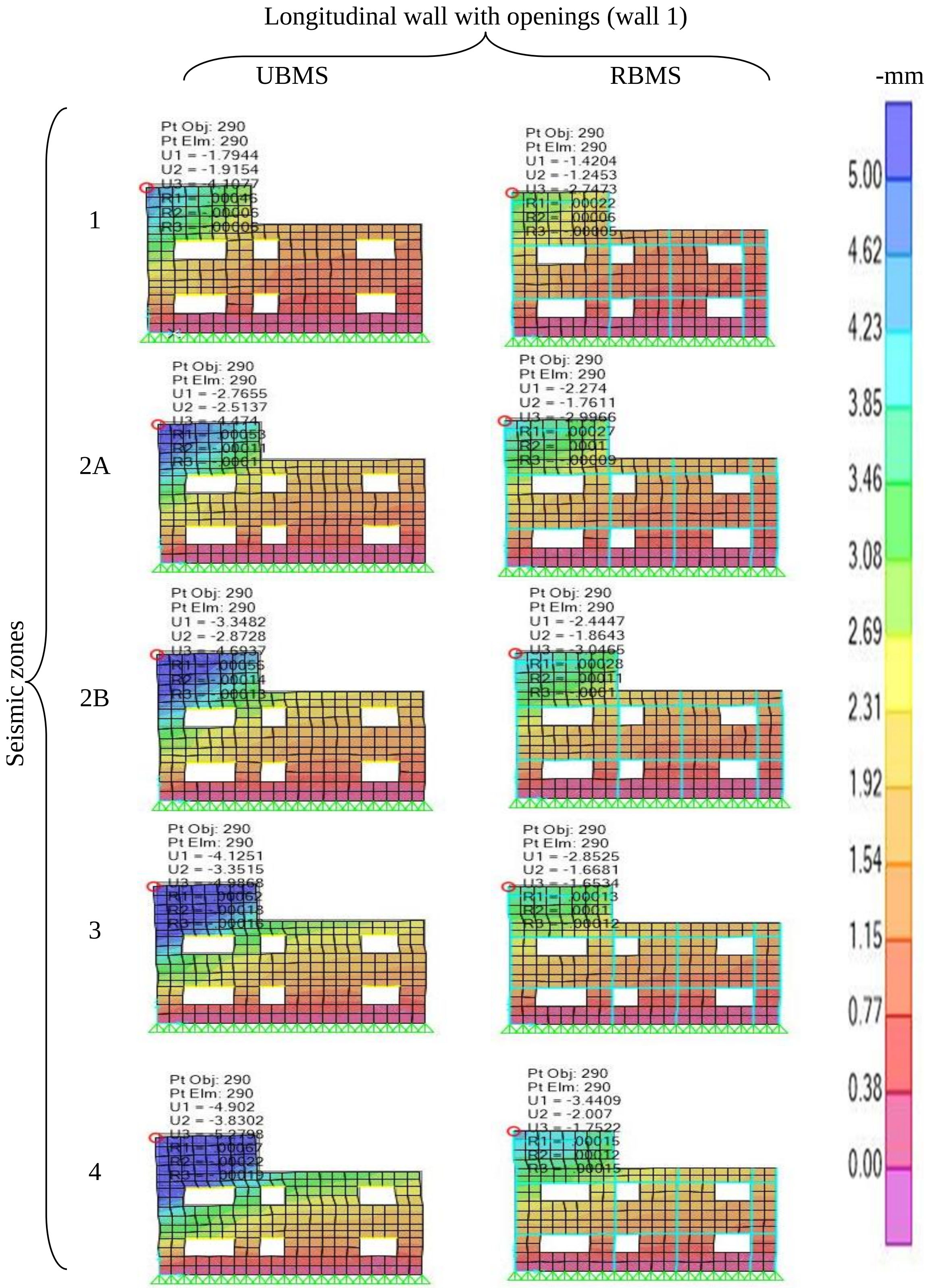


Figure B1: Displacements in longitudinal wall with openings (wall 1) for soil profile type SD and all seismic zones

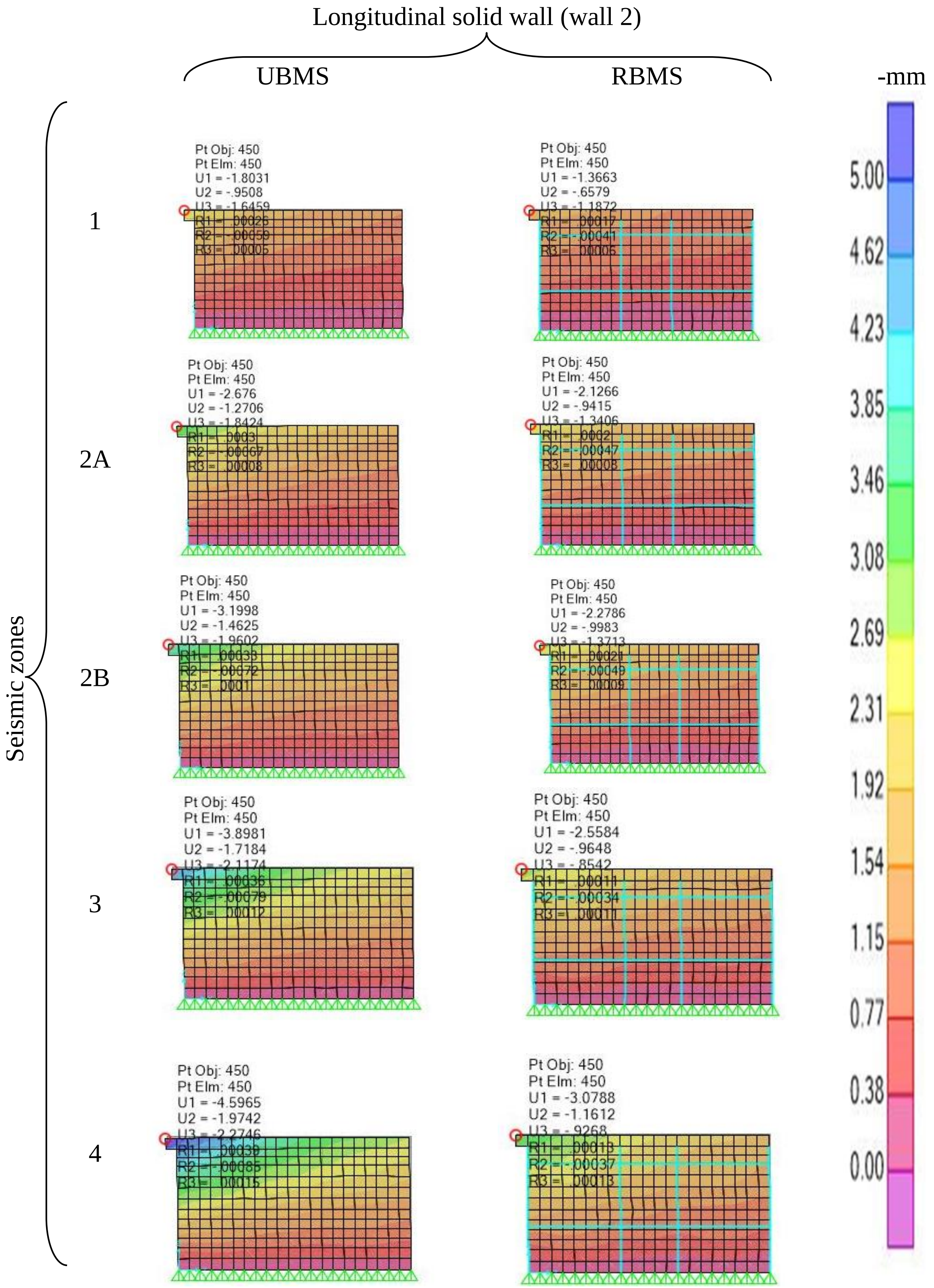


Figure B2: Displacements in longitudinal solid wall (wall 2) for soil profile type SD and all seismic zones

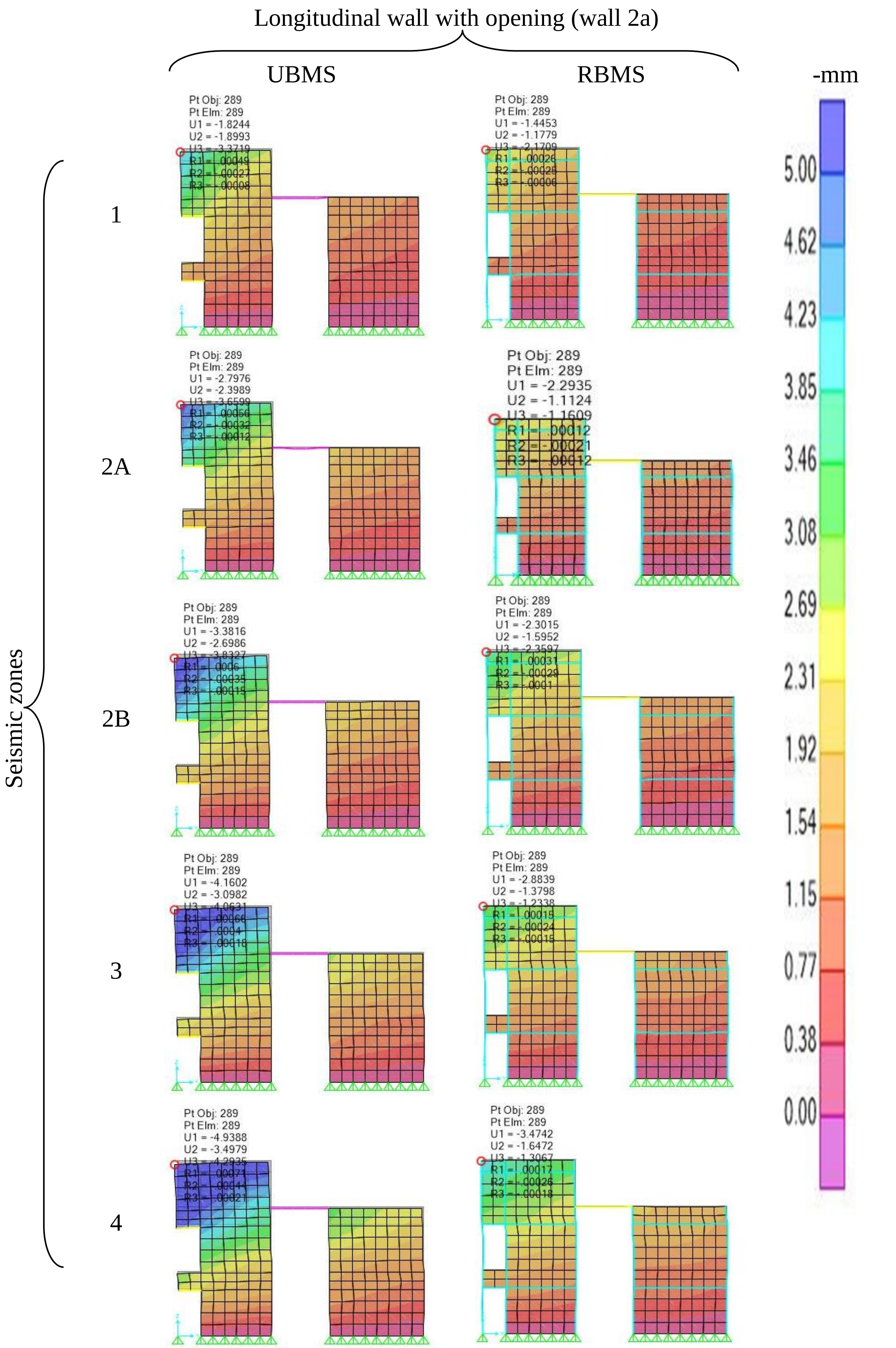


Figure B3: Displacements in longitudinal wall with openings (wall 2a) for soil profile type SD and all seismic zones

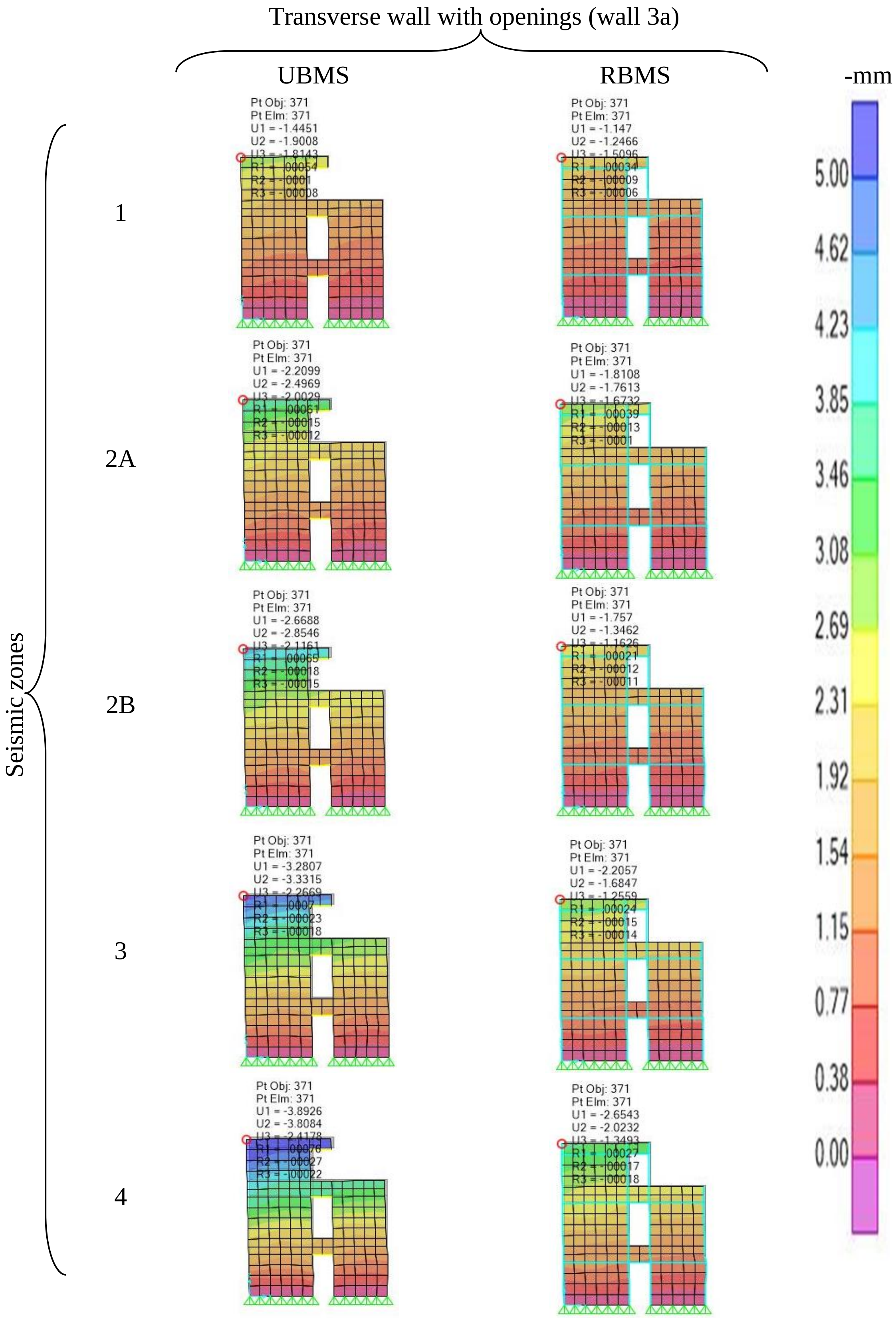


Figure B4: Displacements in transverse wall with openings (wall 3a) for soil profile type SD and all seismic zones

ANNEXURE C

Summary of principle critical stress for other zones in UBMS and RBMS:

Annexure C1

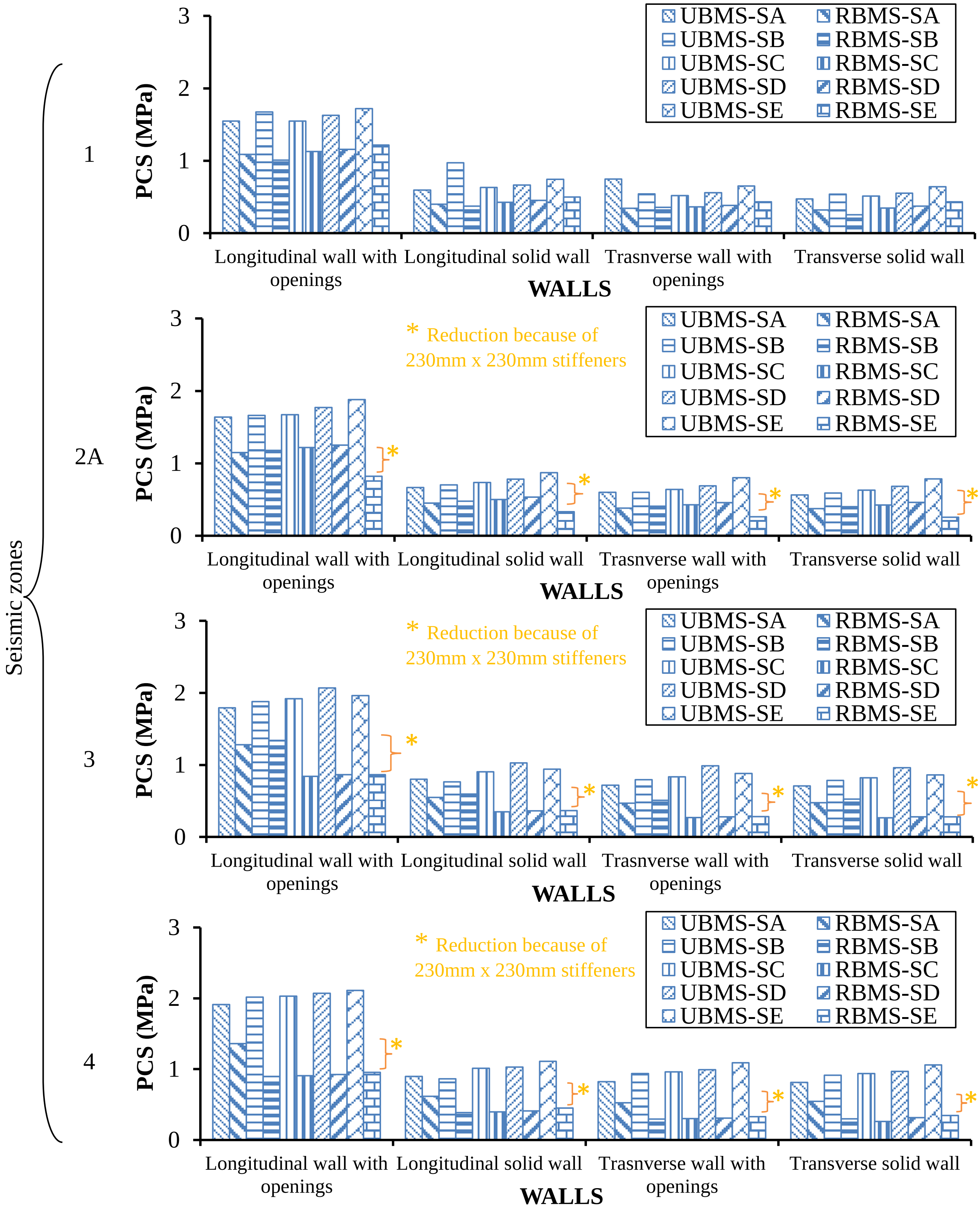


Figure C1: Summary of principal critical stress for zone 1, 2A, 3 and 4 and all soil profile types

ANNEXURE D

Summary of maximum top displacement for other soil profile types in UBMS and RBMS:

Annexure D1

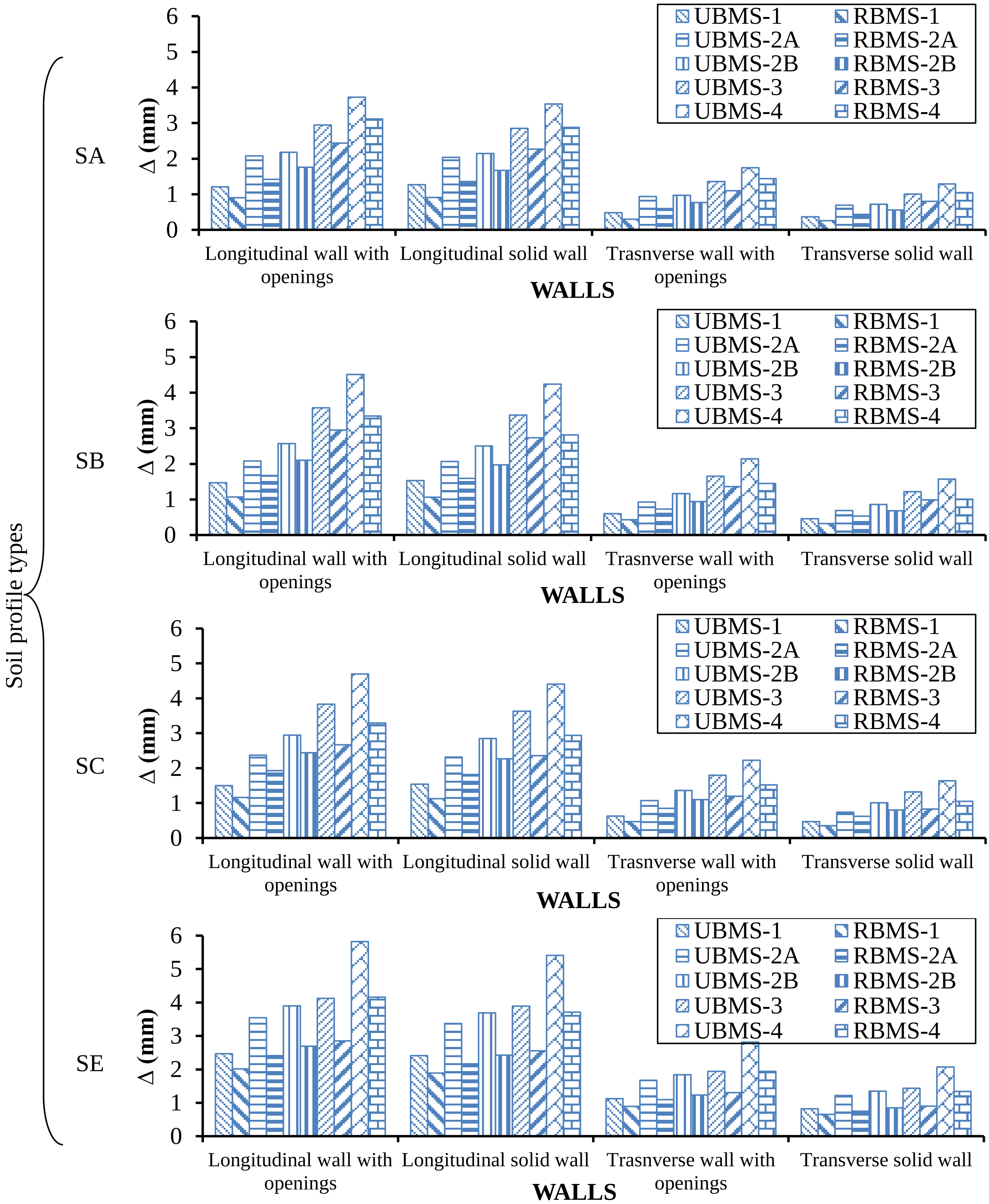


Figure D1: Summary of maximum top displacement for soil profile type SA, SB, SC and SE and all seismic zones

ANNEXURE E

Guidelines for designers to follow for design of brick masonry structures

Annexure E1

Design steps

1. Take the architectural drawings and study in detail.
2. The opening width, opening location, horizontal gap between two openings, opening percentage, lintel level and vertical gap between two openings should be according to the available guidelines for reinforced brick masonry structures mentioned in Annexure E2.
3. The additional considerations i.e. plan and elevation dimensions and brick bonds must be taken into account as detailed in Annexure E3.
4. Identify the locations of stiffeners according to recommendations given in Annexure E4, so as to select the optimum number of stiffeners to start with.
5. As per the soil profile type, seismic zone, importance factor and time period, select the appropriate size of vertical and horizontal stiffeners from Annexure F.
6. Modify the architectural drawings if required keeping in mind steps 2 to 5.
7. Develop the numerical model of reinforced brick masonry structure in SAP2000 according to the modified architectural plans and selected cross-sections of stiffeners to analyze the model and validate the stiffeners.
8. In case, if PCS and Δ exceeds 0.80 MPa and 3 mm, respectively, use the next level cross-section of stiffeners and repeat step 7.
9. Provide typical joint details as per the concept given in Annexure G. The concept may be extended as per the requirement.

Annexure E2

Available guidelines for reinforced brick masonry structures

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:

- *Opening width*: The width of an opening should preferably not be more than 4 ft (1.2 m).
- *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).
- *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).
- *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.
- *Lintel level*: Keep lintels level same for doors and windows.
- *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.

Annexure E3

Additional considerations for planning of brick masonry structure

- The brick size 9" x 4.5" x 3" is standard size and the actual size is little less (approximately 8.5" x 4" x 2.5", assuming 0.5" 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: 4.5" x 4.5" x 3", 9" x 2.25" x 3", 6.75" x 4.5" x 3" and 2.25" x 4.5" x 3" 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 4.5” and 3”, 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 4.5” and 3”, 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.

Annexure E4

Recommendations for locations of stiffeners

Many studies have provided the guidelines for the location of vertical stiffeners. Usually, the vertical stiffeners are provided at corners, at junctions and around openings (doors and windows). 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”. Following this priority, vertical stiffeners around windows may be removed to get the optimum number of vertical stiffeners to start with. The vertical stiffeners locations are selected keeping in mind the safety and economy at the same time.

ANNEXURE F

Proposed diagonal approach for other parameters:

Annexure F1

VERTICAL STIFFENERS

Soil Profile Type	Zone 1	Zone 2A	Zone 2B	Zone 3	Zone 4
Soil Type S_A	fc' = 2500 psi 4½" x 4½" with 1-ϕ2	fc' = 2500 psi 4½" x 4½" with 1-ϕ3	fc' = 2500 psi 4½" x 4½" with 1-ϕ4	fc' = 2500 psi 4½" x 4½" with 1-#3	fc' = 2500 psi 4½" x 4½" with 1-#4
Soil Type S_B	fc' = 2500 psi 4½" x 4½" with 1-ϕ3	fc' = 2500 psi 4½" x 4½" with 1-ϕ4	fc' = 2500 psi 4½" x 4½" with 1-#3	fc' = 2500 psi 4½" x 4½" with 1-#4	fc' = 3000 psi 9" x 9" with re-bars 4-ϕ2 and ties ϕ2 -4.5"/9"
Soil Type S_C	fc' = 2500 psi 4½" x 4½" with 1-ϕ4	fc' = 2500 psi 4½" x 4½" with 1-#3	fc' = 2500 psi 4½" x 4½" with 1-#4	fc' = 3000 psi 9" x 9" with re-bars 4-ϕ2 and ties ϕ2 -4.5"/9"	fc' = 3000 psi 9" x 9" with re-bars 4-ϕ3 and ties ϕ2 -4"/8"
Soil Type S_D	fc' = 2500 psi 4½" x 4½" with 1-#3	fc' = 2500 psi 4½" x 4½" with 1-#4	fc' = 3000 psi 9" x 9" with re-bars 4-ϕ2 and ties ϕ2 -4.5"/9"	fc' = 3000 psi 9" x 9" with re-bars 4-ϕ3 and ties ϕ2 -4"/8"	fc' = 3000 psi 9" x 9" with re-bars 4-ϕ4 and ties ϕ2 -3.5"/7"
Soil Type S_E	fc' = 2500 psi 4½" x 4½" with 1-#4	fc' = 3000 psi 9" x 9" with re-bars 4-ϕ2 and ties ϕ2 -4.5"/9"	fc' = 3000 psi 9" x 9" with re-bars 4-ϕ3 and ties ϕ2 -4"/8"	fc' = 3000 psi 9" x 9" with re-bars 4-ϕ4 and ties ϕ2 -3.5"/7"	fc' = 3000 psi 9" x 9" with re-bars 4-#3 and ties ϕ 3 -4.5"/9"

HORIZONTAL STIFFENERS

Soil Profile Type	Zone 1	Zone 2A	Zone 2B	Zone 3	Zone 4
Soil Type S_A	fc' = 2500 psi 9" x 3" with re-bars 2-ϕ2 and stirrups ϕ2 -8"	fc' = 2500 psi 9" x 3" with re-bars 2-ϕ3 and stirrups ϕ2 -6"	fc' = 2500 psi 9" x 3" with re-bars 2-ϕ4 and stirrups ϕ2 -4"	fc' = 2500 psi 9" x 3" with re-bars 2-#3 and stirrups ϕ3 -8"	fc' = 2500 psi 9" x 3" with re-bars 2-#4 and stirrups ϕ3 -6"
Soil Type S_B	fc' = 2500 psi 9" x 3" with re-bars 2-ϕ3 and stirrups ϕ2 -6"	fc' = 2500 psi 9" x 3" with re-bars 2-ϕ4 and stirrups ϕ2 -4"	fc' = 2500 psi 9" x 3" with re-bars 2-#3 and stirrups ϕ3 -8"	fc' = 2500 psi 9" x 3" with re-bars 2-#4 and stirrups ϕ3 -6"	fc' = 3000 psi 9" x 6" with re-bars 4-ϕ2 and stirrups ϕ2 -8"
Soil Type S_C	fc' = 2500 psi 9" x 3" with re-bars 2-ϕ4 and stirrups ϕ2 -4"	fc' = 2500 psi 9" x 3" with re-bars 2-#3 and stirrups ϕ3 -8"	fc' = 2500 psi 9" x 3" with re-bars 2-#4 and stirrups ϕ3 -6"	fc' = 3000 psi 9" x 6" with re-bars 4-ϕ2 and stirrups ϕ2 -8"	fc' = 3000 psi 9" x 6" with re-bars 4-ϕ3 and stirrups ϕ2 -6"
Soil Type S_D	fc' = 2500 psi 9" x 3" with re-bars 2-#3 and stirrups ϕ3 -8"	fc' = 2500 psi 9" x 3" with re-bars 2-#4 and stirrups ϕ3 -6"	fc' = 3000 psi 9" x 6" with re-bars 4-ϕ2 and stirrups ϕ2 -8"	fc' = 3000 psi 9" x 6" with re-bars 4-ϕ3 and stirrups ϕ2 -6"	fc' = 3000 psi 9" x 6" with re-bars 4-ϕ4 and stirrups ϕ2 -4"
Soil Type S_E	fc' = 2500 psi 9" x 3" with re-bars 2-#4 and stirrups ϕ3 -6"	fc' = 3000 psi 9" x 6" with re-bars 4-ϕ2 and stirrups ϕ2 -8"	fc' = 3000 psi 9" x 6" with re-bars 4-ϕ3 and stirrups ϕ2 -6"	fc' = 3000 psi 9" x 6" with re-bars 4-ϕ4 and stirrups ϕ2 -4"	fc' = 3000 psi 9" x 6" with re-bars 4-#3 and stirrups ϕ3 -8"

Figure E1: Cross-sectional details of RC vertical and horizontal stiffeners for different seismic zones and soil types with I = 1 and T $\leq$ 0.7s (FPS details)

	Soil Profile Type	Zone 1	Zone 2A	Zone 2B	Zone 3	Zone 4
VERTICAL STIFFENERS	**Soil Type S_A**	fc’ = 2500 psi 4½” x 4½” with 1-ϕ3	fc’ = 2500 psi 4½” x 4½” with 1-ϕ4	fc’ = 2500 psi 4½” x 4½” with 1-#3	fc’ = 2500 psi 4½” x 4½” with 1-#4	fc’ = 3000 psi 9” x 9” with re-bars 4-ϕ2 and ties ϕ2 -4.5”/9”
	Soil Type S_B	fc’ = 2500 psi 4½” x 4½” with 1-ϕ4	fc’ = 2500 psi 4½” x 4½” with 1-#3	fc’ = 2500 psi 4½” x 4½” with 1-#4	fc’ = 3000 psi 9” x 9” with re-bars 4-ϕ2 and ties ϕ2 -4.5”/9”	fc’ = 3000 psi 9” x 9” with re-bars 4-ϕ3 and ties ϕ2 -4”/8”
	Soil Type S_C	fc’ = 2500 psi 4½” x 4½” with 1-#3	fc’ = 2500 psi 4½” x 4½” with 1-#4	fc’ = 3000 psi 9” x 9” with re-bars 4-ϕ2 and ties ϕ2 -4.5”/9”	fc’ = 3000 psi 9” x 9” with re-bars 4-ϕ3 and ties ϕ2 -4”/8”	fc’ = 3000 psi 9” x 9” with re-bars 4-ϕ4 and ties ϕ2 -3.5”/7”
	Soil Type S_D	fc’ = 2500 psi 4½” x 4½” with 1-#4	fc’ = 3000 psi 9” x 9” with re-bars 4-ϕ2 and ties ϕ2 -4.5”/9”	fc’ = 3000 psi 9” x 9” with re-bars 4-ϕ3 and ties ϕ2 -4”/8”	fc’ = 3000 psi 9” x 9” with re-bars 4-ϕ4 and ties ϕ2 -3.5”/7”	fc’ = 3000 psi 9” x 9” with re-bars 4-#3 and ties ϕ 3 -4.5”/9”
	Soil Type S_E	fc’ = 3000 psi 9” x 9” with re-bars 4-ϕ2 and ties ϕ2 -4.5”/9”	fc’ = 3000 psi 9” x 9” with re-bars 4-ϕ3 and ties ϕ2 -4”/8”	fc’ = 3000 psi 9” x 9” with re-bars 4-ϕ4 and ties ϕ2 -3.5”/7”	fc’ = 3000 psi 9” x 9” with re-bars 4-#3 and ties ϕ 3 -4.5”/9”	fc’ = 3000 psi 9” x 9” with re-bars 4-#4 and ties ϕ 3 -4”/8”
	Soil Profile Type	**Zone 1**	**Zone 2A**	**Zone 2B**	**Zone 3**	**Zone 4**
HORIZONTAL STIFFENERS	**Soil Type S_A**	fc’ = 2500 psi 9” x 3” with re-bars 2-ϕ3 and stirrups ϕ2 -6”	fc’ = 2500 psi 9” x 3” with re-bars 2-ϕ4 and stirrups ϕ2 -4”	fc’ = 2500 psi 9” x 3” with re-bars 2-#3 and stirrups ϕ3 -8”	fc’ = 2500 psi 9” x 3” with re-bars 2-#4 and stirrups ϕ3 -6”	fc’ = 3000 psi 9” x 6” with re-bars 4-ϕ2 and stirrups ϕ2 -8”
	Soil Type S_B	fc’ = 2500 psi 9” x 3” with re-bars 2-ϕ4 and stirrups ϕ2 -4”	fc’ = 2500 psi 9” x 3” with re-bars 2-#3 and stirrups ϕ3 -8”	fc’ = 2500 psi 9” x 3” with re-bars 2-#4 and stirrups ϕ3 -6”	fc’ = 3000 psi 9” x 6” with re-bars 4-ϕ2 and stirrups ϕ2 -8”	fc’ = 3000 psi 9” x 6” with re-bars 4-ϕ3 and stirrups ϕ2 -6”
	Soil Type S_C	fc’ = 2500 psi 9” x 3” with re-bars 2-#3 and stirrups ϕ3 -8”	fc’ = 2500 psi 9” x 3” with re-bars 2-#4 and stirrups ϕ3 -6”	fc’ = 3000 psi 9” x 6” with re-bars 4-ϕ2 and stirrups ϕ2 -8”	fc’ = 3000 psi 9” x 6” with re-bars 4-ϕ3 and stirrups ϕ2 -6”	fc’ = 3000 psi 9” x 6” with re-bars 4-ϕ4 and stirrups ϕ2 -4”
	Soil Type S_D	fc’ = 2500 psi 9” x 3” with re-bars 2-#4 and stirrups ϕ3 -6”	fc’ = 3000 psi 9” x 6” with re-bars 4-ϕ2 and stirrups ϕ2 -8”	fc’ = 3000 psi 9” x 6” with re-bars 4-ϕ3 and stirrups ϕ2 -6”	fc’ = 3000 psi 9” x 6” with re-bars 4-ϕ4 and stirrups ϕ2 -4”	fc’ = 3000 psi 9” x 6” with re-bars 4-#3 and stirrups ϕ3 -8”
	Soil Type S_E	fc’ = 3000 psi 9” x 6” with re-bars 4-ϕ2 and stirrups ϕ2 -8”	fc’ = 3000 psi 9” x 6” with re-bars 4-ϕ3 and stirrups ϕ2 -6”	fc’ = 3000 psi 9” x 6” with re-bars 4-ϕ4 and stirrups ϕ2 -4”	fc’ = 3000 psi 9” x 6” with re-bars 4-#3 and stirrups ϕ3 -8”	fc’ = 3000 psi 9” x 6” with re-bars 4-#4 and stirrups ϕ3–6”

Figure E2: Cross-sectional details of RC vertical and horizontal stiffeners for different seismic zones and soil types with I = 1 and T > 0.7 or I = 1.25 and T $\leq$ 0.7s (FPS details)

VERTICAL STIFFENERS

Soil Profile Type	Zone 1	Zone 2A	Zone 2B	Zone 3	Zone 4
Soil Type S_A	fc’ = 2500 psi 4½” x 4½” with 1-ϕ4	fc’ = 2500 psi 4½” x 4½” with 1-#3	fc’ = 2500 psi 4½” x 4½” with 1-#4	fc’ = 3000 psi 9” x 9” with re-bars 4-ϕ2 and ties ϕ2 -4.5”/9”	fc’ = 3000 psi 9” x 9” with re-bars 4-ϕ3 and ties ϕ2 -4”/8”
Soil Type S_B	fc’ = 2500 psi 4½” x 4½” with 1-#3	fc’ = 2500 psi 4½” x 4½” with 1-#4	fc’ = 3000 psi 9” x 9” with re-bars 4-ϕ2 and ties ϕ2 -4.5”/9”	fc’ = 3000 psi 9” x 9” with re-bars 4-ϕ3 and ties ϕ2 -4”/8”	fc’ = 3000 psi 9” x 9” with re-bars 4-ϕ4 and ties ϕ2 -3.5”/7”
Soil Type S_C	fc’ = 2500 psi 4½” x 4½” with 1-#4	fc’ = 3000 psi 9” x 9” with re-bars 4-ϕ2 and ties ϕ2 -4.5”/9”	fc’ = 3000 psi 9” x 9” with re-bars 4-ϕ3 and ties ϕ2 -4”/8”	fc’ = 3000 psi 9” x 9” with re-bars 4-ϕ4 and ties ϕ2 -3.5”/7”	fc’ = 3000 psi 9” x 9” with re-bars 4-#3 and ties ϕ 3 -4.5”/9”
Soil Type S_D	fc’ = 3000 psi 9” x 9” with re-bars 4-ϕ2 and ties ϕ2 -4.5”/9”	fc’ = 3000 psi 9” x 9” with re-bars 4-ϕ3 and ties ϕ2 -4”/8”	fc’ = 3000 psi 9” x 9” with re-bars 4-ϕ4 and ties ϕ2 -3.5”/7”	fc’ = 3000 psi 9” x 9” with re-bars 4-#3 and ties ϕ 3 -4.5”/9”	fc’ = 3000 psi 9” x 9” with re-bars 4-#4 and ties ϕ 3 -4”/8”
Soil Type S_E	fc’ = 3000 psi 9” x 9” with re-bars 4-ϕ3 and ties ϕ2 -4”/8”	fc’ = 3000 psi 9” x 9” with re-bars 4-ϕ4 and ties ϕ2 -3.5”/7”	fc’ = 3000 psi 9” x 9” with re-bars 4-#3 and ties ϕ 3 -4.5”/9”	fc’ = 3000 psi 9” x 9” with re-bars 4-#4 and ties ϕ 3 -4”/8”	fc’ = 3000 psi 9” x 9” with re-bars 4-#5 and ties ϕ 3 -3.5”/7”

HORIZONTAL STIFFENERS

Soil Profile Type	Zone 1	Zone 2A	Zone 2B	Zone 3	Zone 4
Soil Type S_A	fc’ = 2500 psi 9” x 3” with re-bars 2-ϕ4 and stirrups ϕ2 -4”	fc’ = 2500 psi 9” x 3” with re-bars 2-#3 and stirrups ϕ3 -8”	fc’ = 2500 psi 9” x 3” with re-bars 2-#4 and stirrups ϕ3 -6”	fc’ = 3000 psi 9” x 6” with re-bars 4-ϕ2 and stirrups ϕ2 -8”	fc’ = 3000 psi 9” x 6” with re-bars 4-ϕ3 and stirrups ϕ2 -6”
Soil Type S_B	fc’ = 2500 psi 9” x 3” with re-bars 2-#3 and stirrups ϕ3 -8”	fc’ = 2500 psi 9” x 3” with re-bars 2-#4 and stirrups ϕ3 -6”	fc’ = 3000 psi 9” x 6” with re-bars 4-ϕ2 and stirrups ϕ2 -8”	fc’ = 3000 psi 9” x 6” with re-bars 4-ϕ3 and stirrups ϕ2 -6”	fc’ = 3000 psi 9” x 6” with re-bars 4-ϕ4 and stirrups ϕ2 -4”
Soil Type S_C	fc’ = 2500 psi 9” x 3” with re-bars 2-#4 and stirrups ϕ3 -6”	fc’ = 3000 psi 9” x 6” with re-bars 4-ϕ2 and stirrups ϕ2 -8”	fc’ = 3000 psi 9” x 6” with re-bars 4-ϕ3 and stirrups ϕ2 -6”	fc’ = 3000 psi 9” x 6” with re-bars 4-ϕ4 and stirrups ϕ2 -4”	fc’ = 3000 psi 9” x 6” with re-bars 4-#3 and stirrups ϕ3 -8”
Soil Type S_D	fc’ = 3000 psi 9” x 6” with re-bars 4-ϕ2 and stirrups ϕ2 -8”	fc’ = 3000 psi 9” x 6” with re-bars 4-ϕ3 and stirrups ϕ2 -6”	fc’ = 3000 psi 9” x 6” with re-bars 4-ϕ4 and stirrups ϕ2 -4”	fc’ = 3000 psi 9” x 6” with re-bars 4-#3 and stirrups ϕ3 -8”	fc’ = 3000 psi 9” x 6” with re-bars 4-#4 and stirrups ϕ3 –6”
Soil Type S_E	fc’ = 3000 psi 9” x 6” with re-bars 4-ϕ3 and stirrups ϕ2 -6”	fc’ = 3000 psi 9” x 6” with re-bars 4-ϕ4 and stirrups ϕ2 -4”	fc’ = 3000 psi 9” x 6” with re-bars 4-#3 and stirrups ϕ3 -8”	fc’ = 3000 psi 9” x 6” with re-bars 4-#4 and stirrups ϕ3 –6”	fc’ = 3000 psi 9” x 6” with re-bars 4-#5 and stirrups ϕ3 -4”

Figure E3: Cross-sectional details of RC vertical and horizontal stiffeners for different seismic zones and soil types with I = 1.25 and T > 0.7s (FPS details)

	Soil Profile Type	Zone 4		
		Na = 1 & Nv = 1.2	**Na = 1.3 & Nv = 1.6**	**Na = 1.5 & Nv = 2**
VERTICAL STIFFENERS	**Soil Type S_A**	fc’ = 3000 psi 9” x 9” with re-bars 4-ϕ2 and ties ϕ2 -4.5”/9”	fc’ = 3000 psi 9” x 9” with re-bars 4-ϕ3 and ties ϕ2 -4”/8”	fc’ = 3000 psi 9” x 9” with re-bars 4-ϕ4 and ties ϕ2 -3.5”/7”
	Soil Type S_B	fc’ = 3000 psi 9” x 9” with re-bars 4-ϕ3 and ties ϕ2 -4”/8”	fc’ = 3000 psi 9” x 9” with re-bars 4-ϕ4 and ties ϕ2 -3.5”/7”	fc’ = 3000 psi 9” x 9” with re-bars 4-#3 and ties ϕ 3 -4.5”/9”
	Soil Type S_C	fc’ = 3000 psi 9” x 9” with re-bars 4-ϕ4 and ties ϕ2 -3.5”/7”	fc’ = 3000 psi 9” x 9” with re-bars 4-#3 and ties ϕ 3 -4.5”/9”	fc’ = 3000 psi 9” x 9” with re-bars 4-#4 and ties ϕ 3 -4”/8”
	Soil Type S_D	fc’ = 3000 psi 9” x 9” with re-bars 4-#3 and ties ϕ 3 -4.5”/9”	fc’ = 3000 psi 9” x 9” with re-bars 4-#4 and ties ϕ 3 -4”/8”	fc’ = 3000 psi 9” x 9” with re-bars 4-#5 and ties ϕ 3 -3.5”/7”
	Soil Type S_E	fc’ = 3000 psi 9” x 9” with re-bars 4-#4 and ties ϕ 3 -4”/8”	fc’ = 3000 psi 9” x 9” with re-bars 4-#5 and ties ϕ 3 -3.5”/7”	fc’ = 3000 psi 13.5” x 9” with re-bars 6-#3 and ties #3-4.5”/9”

	Soil Profile Type	Zone 4		
		Na = 1 & Nv = 1.2	**Na = 1.3 & Nv = 1.6**	**Na = 1.5 & Nv = 2**
HORIZONTAL STIFFENERS	**Soil Type S_A**	fc’ = 3000 psi 9” x 6” with re-bars 4-ϕ2 and stirrups ϕ2 -8”	fc’ = 3000 psi 9” x 6” with re-bars 4-ϕ3 and stirrups ϕ2 -6”	fc’ = 3000 psi 9” x 6” with re-bars 4-ϕ4 and stirrups ϕ2 -4”
	Soil Type S_B	fc’ = 3000 psi 9” x 6” with re-bars 4-ϕ3 and stirrups ϕ2 -6”	fc’ = 3000 psi 9” x 6” with re-bars 4-ϕ4 and stirrups ϕ2 -4”	fc’ = 3000 psi 9” x 6” with re-bars 4-#3 and stirrups ϕ3 -8”
	Soil Type S_C	fc’ = 3000 psi 9” x 6” with re-bars 4-ϕ4 and stirrups ϕ2 -4”	fc’ = 3000 psi 9” x 6” with re-bars 4-#3 and stirrups ϕ3 -8”	fc’ = 3000 psi 9” x 6” with re-bars 4-#4 and stirrups ϕ3–6”
	Soil Type S_D	fc’ = 3000 psi 9” x 6” with re-bars 4-#3 and stirrups ϕ3 -8”	fc’ = 3000 psi 9” x 6” with re-bars 4-#4 and stirrups ϕ3–6”	fc’ = 3000 psi 9” x 6” with re-bars 4-#5 and stirrups ϕ3 -4”
	Soil Type S_E	fc’ = 3000 psi 9” x 6” with re-bars 4-#4 and stirrups ϕ3–6”	fc’ = 3000 psi 9” x 6” with re-bars 4-#5 and stirrups ϕ3 -4”	fc’ = 3000 psi 9” x 9” with re-bars 4-#3 and stirrups #3 -8”

Figure E4: Cross-sectional details of RC vertical and horizontal stiffeners for different near source factors (> 1) and soil types in seismic 4 with $I = 1$ *and* $T \leq 0.7s$ (FPS details)

	Soil Profile Type	Zone 4 Na = 1 & Nv = 1.2	Zone 4 Na = 1.3 & Nv = 1.6	Zone 4 Na = 1.5 & Nv = 2
VERTICAL STIFFENERS	**Soil Type S_A**	fc' = 3000 psi 9" x 9" with re-bars 4-ϕ3 and ties ϕ2 -4"/8"	fc' = 3000 psi 9" x 9" with re-bars 4-ϕ4 and ties ϕ2 -3.5"/7"	fc' = 3000 psi 9" x 9" with re-bars 4-#3 and ties ϕ 3 -4.5"/9"
	Soil Type S_B	fc' = 3000 psi 9" x 9" with re-bars 4-ϕ4 and ties ϕ2 -3.5"/7"	fc' = 3000 psi 9" x 9" with re-bars 4-#3 and ties ϕ 3 -4.5"/9"	fc' = 3000 psi 9" x 9" with re-bars 4-#4 and ties ϕ 3 -4"/8"
	Soil Type S_C	fc' = 3000 psi 9" x 9" with re-bars 4-#3 and ties ϕ 3 -4.5"/9"	fc' = 3000 psi 9" x 9" with re-bars 4-#4 and ties ϕ 3 -4"/8"	fc' = 3000 psi 9" x 9" with re-bars 4-#5 and ties ϕ 3 -3.5"/7"
	Soil Type S_D	fc' = 3000 psi 9" x 9" with re-bars 4-#4 and ties ϕ 3 -4"/8"	fc' = 3000 psi 9" x 9" with re-bars 4-#5 and ties ϕ 3 -3.5"/7"	fc' = 3000 psi 13.5" x 9" with re-bars 6-#3 and ties #3-4.5"/9"
	Soil Type S_E	fc' = 3000 psi 9" x 9" with re-bars 4-#5 and ties ϕ 3 -3.5"/7"	fc' = 3000 psi 13.5" x 9" with re-bars 6-#3 and ties #3-4.5"/9"	fc' = 3000 psi 13.5" x 9" with re-bars 6-#4 and ties #3 -4"/8"

	Soil Profile Type	Zone 4 Na = 1 & Nv = 1.2	Zone 4 Na = 1.3 & Nv = 1.6	Zone 4 Na = 1.5 & Nv = 2
HORIZONTAL STIFFENERS	**Soil Type S_A**	fc' = 3000 psi 9" x 6" with re-bars 4-ϕ3 and stirrups ϕ2 -6"	fc' = 3000 psi 9" x 6" with re-bars 4-ϕ4 and stirrups ϕ2 -4"	fc' = 3000 psi 9" x 6" with re-bars 4-#3 and stirrups ϕ3 -8"
	Soil Type S_B	fc' = 3000 psi 9" x 6" with re-bars 4-ϕ4 and stirrups ϕ2 -4"	fc' = 3000 psi 9" x 6" with re-bars 4-#3 and stirrups ϕ3 -8"	fc' = 3000 psi 9" x 6" with re-bars 4-#4 and stirrups ϕ3 –6"
	Soil Type S_C	fc' = 3000 psi 9" x 6" with re-bars 4-#3 and stirrups ϕ3 -8"	fc' = 3000 psi 9" x 6" with re-bars 4-#4 and stirrups ϕ3 –6"	fc' = 3000 psi 9" x 6" with re-bars 4-#5 and stirrups ϕ3 -4"
	Soil Type S_D	fc' = 3000 psi 9" x 6" with re-bars 4-#4 and stirrups ϕ3 –6"	fc' = 3000 psi 9" x 6" with re-bars 4-#5 and stirrups ϕ3 -4"	fc' = 3000 psi 9" x 9" with re-bars 4-#3 and stirrups #3 -8"
	Soil Type S_E	fc' = 3000 psi 9" x 6" with re-bars 4-#5 and stirrups ϕ3 -4"	fc' = 3000 psi 9" x 9" with re-bars 4-#3 and stirrups #3 -8"	fc' = 3000 psi 9" x 9" with re-bars 4-#4 and stirrups #3 -6"

Figure E5: Cross-sectional details of RC vertical and horizontal stiffeners for different near source factors (> 1) and soil types in seismic 4 with *I = 1 and T > 0.7* or *I = 1.25 and T ≤ 0.7s* (FPS details)

	Soil Profile Type	Zone 4		
		Na = 1 & Nv = 1.2	Na = 1.3 & Nv = 1.6	Na = 1.5 & Nv = 2
VERTICAL STIFFENERS	Soil Type S_A	fc' = 3000 psi 9" x 9" with re-bars 4-ϕ4 and ties ϕ2 -3.5"/7"	fc' = 3000 psi 9" x 9" with re-bars 4-#3 and ties ϕ 3 -4.5"/9"	fc' = 3000 psi 9" x 9" with re-bars 4-#4 and ties ϕ 3 -4"/8"
	Soil Type S_B	fc' = 3000 psi 9" x 9" with re-bars 4-#3 and ties ϕ 3 -4.5"/9"	fc' = 3000 psi 9" x 9" with re-bars 4-#4 and ties ϕ 3 -4"/8"	fc' = 3000 psi 9" x 9" with re-bars 4-#5 and ties ϕ 3 -3.5"/7"
	Soil Type S_C	fc' = 3000 psi 9" x 9" with re-bars 4-#4 and ties ϕ 3 -4"/8"	fc' = 3000 psi 9" x 9" with re-bars 4-#5 and ties ϕ 3 -3.5"/7"	fc' = 3000 psi 13.5" x 9" with re-bars 6-#3 and ties #3-4.5"/9"
	Soil Type S_D	fc' = 3000 psi 9" x 9" with re-bars 4-#5 and ties ϕ 3 -3.5"/7"	fc' = 3000 psi 13.5" x 9" with re-bars 6-#3 and ties #3-4.5"/9"	fc' = 3000 psi 13.5" x 9" with re-bars 6-#4 and ties #3 -4"/8"
	Soil Type S_E	fc' = 3000 psi 13.5" x 9" with re-bars 6-#3 and ties #3-4.5"/9"	fc' = 3000 psi 13.5" x 9" with re-bars 6-#4 and ties #3 -4"/8"	fc' = 3000 psi 13.5" x 9" with re-bars 6-#5 and ties #3 -3.5"/7"

	Soil Profile Type	Zone 4		
		Na = 1 & Nv = 1.2	Na = 1.3 & Nv = 1.6	Na = 1.5 & Nv = 2
HORIZONTAL STIFFENERS	Soil Type S_A	fc' = 3000 psi 9" x 6" with re-bars 4-ϕ4 and stirrups ϕ2 -4"	fc' = 3000 psi 9" x 6" with re-bars 4-#3 and stirrups ϕ3 -8"	fc' = 3000 psi 9" x 6" with re-bars 4-#4 and stirrups ϕ3 –6"
	Soil Type S_B	fc' = 3000 psi 9" x 6" with re-bars 4-#3 and stirrups ϕ3 -8"	fc' = 3000 psi 9" x 6" with re-bars 4-#4 and stirrups ϕ3 –6"	fc' = 3000 psi 9" x 6" with re-bars 4-#5 and stirrups ϕ3 -4"
	Soil Type S_C	fc' = 3000 psi 9" x 6" with re-bars 4-#4 and stirrups ϕ3 –6"	fc' = 3000 psi 9" x 6" with re-bars 4-#5 and stirrups ϕ3 -4"	fc' = 3000 psi 9" x 9" with re-bars 4-#3 and stirrups #3 -8"
	Soil Type S_D	fc' = 3000 psi 9" x 6" with re-bars 4-#5 and stirrups ϕ3 -4"	fc' = 3000 psi 9" x 9" with re-bars 4-#3 and stirrups #3 -8"	fc' = 3000 psi 9" x 9" with re-bars 4-#4 and stirrups #3 -6"
	Soil Type S_E	fc' = 3000 psi 9" x 9" with re-bars 4-#3 and stirrups #3 -8"	fc' = 3000 psi 9" x 9" with re-bars 4-#4 and stirrups #3 -6"	fc' = 3000 psi 9" x 9" with re-bars 4-#5 and stirrups #3 -4"

Figure E6: Cross-sectional details of RC vertical and horizontal stiffeners for different near source factors (> 1) and soil types in seismic 4 with $I = 1.25$ *and* $T > 0.7s$ (FPS details)

ANNEXURE G

Joint details of vertical and horizontal stiffeners

ANNEXURE G1

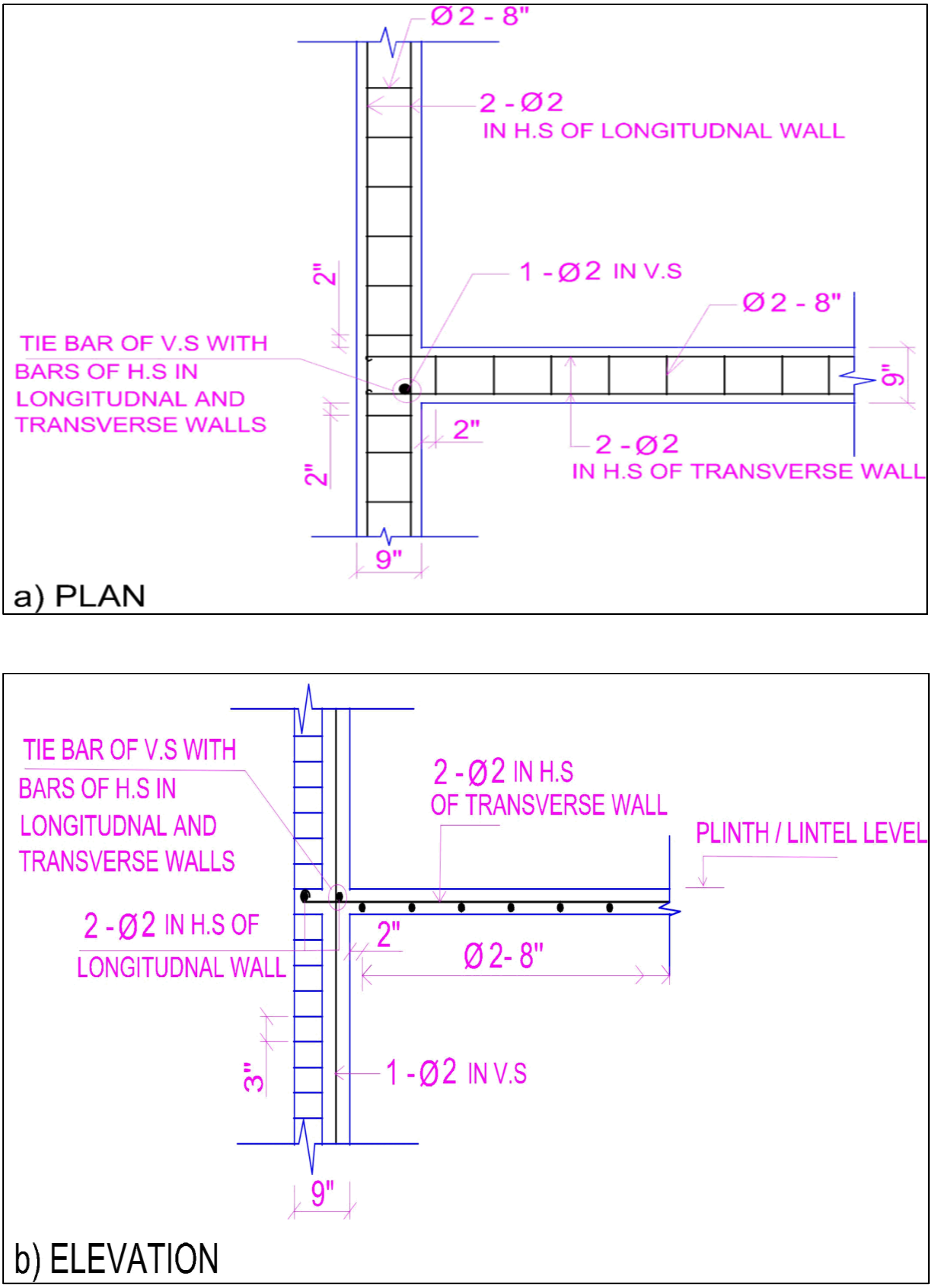
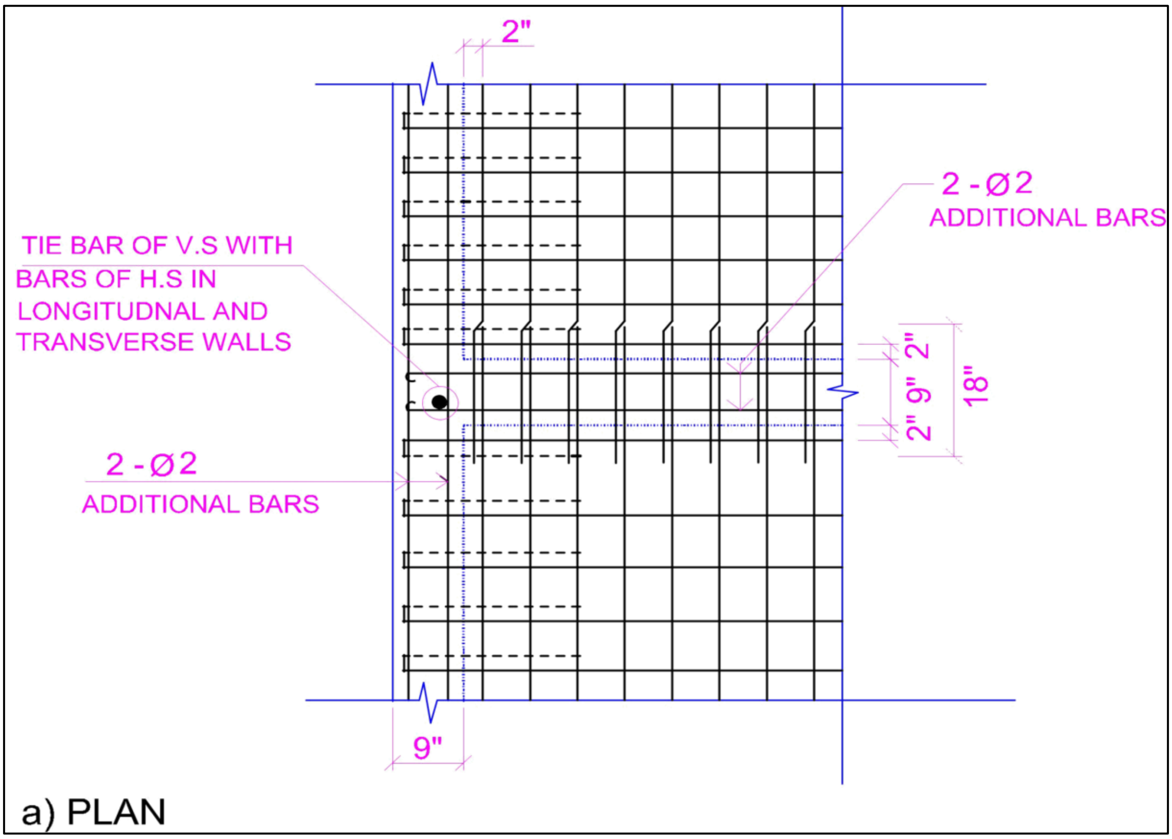


Figure G1: Details at joint junction (at plinth and lintel levels) with H.S and V.S of soil profile type "SA" and seismic zone "1": (a) PLAN (b) ELEVATION



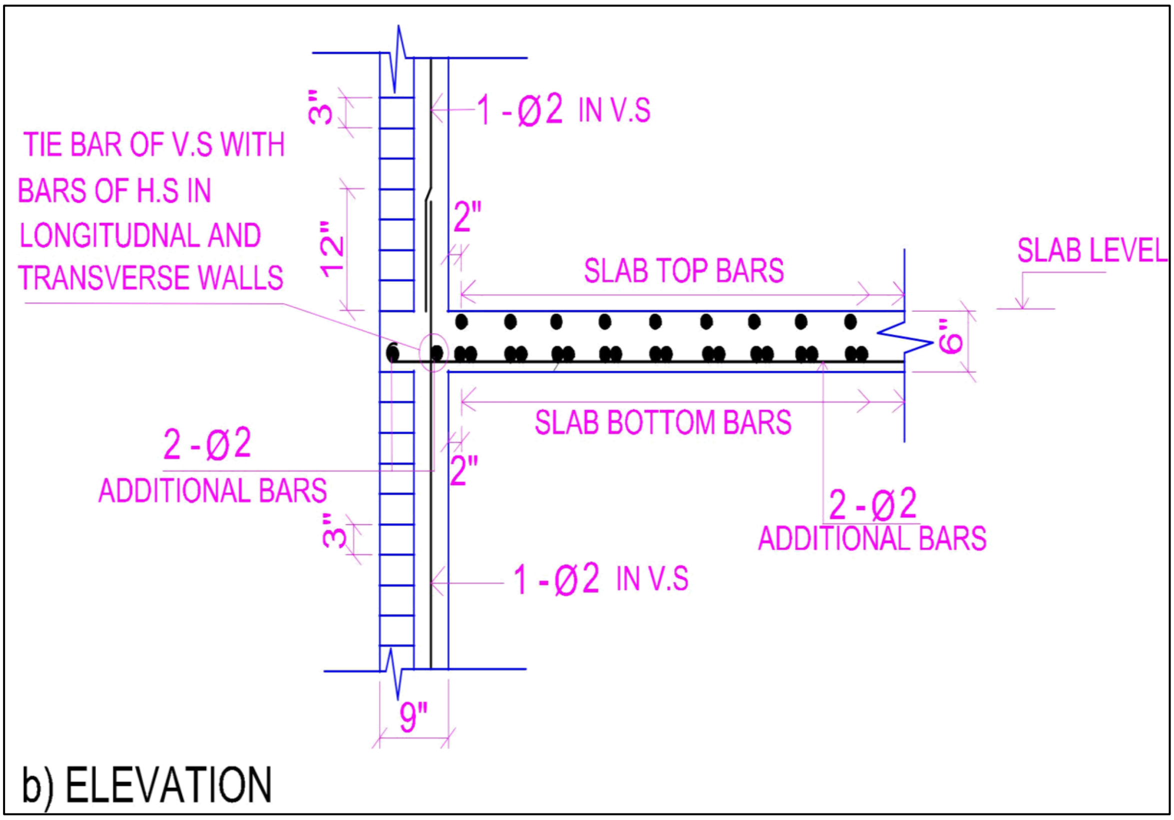


Figure G2: Details at joint junction (at slab level) with soil profile type "SA" and seismic zone "1": (a) PLAN (b) ELEVATION