EFFECTS OF MORTAR THICKNESS AND MORTAR STRENGTH ON IN-PLANE AND OUT-OF-PLANE BEHAVIOR OF BRICK MASONRY WALLS

N. Saxena(1), S. Lala(2), K.S. Kulkarni(3)

(1) Senior Principal Scientist, CSIR-Central Building Research Institute, Roorkee, navjeevsaxena@gmail.com
(2) Scientist, CSIR-Central Building Research Institute, Roorkee, sayantani.lala@gmail.com
(3) Scientist, CSIR-Central Building Research Institute, Roorkee, kishorsk1@gmail.com

Abstract

Behavior assessment of brick masonry walls is an involving task due to its anisotropic mechanical properties due to mortar joints. The constituent materials bricks, mortar and the type of masonry bond govern the behavior. Large-scale past damages in masonry structures after major earthquake reveal that prominently it is due to the failure of brick-joint interfaces. Contribution of Brick-joint interface depends on the thickness of interface made of mortar and the mortar strength. Reddy et. al. [1] conducted tests on masonry prisms and concluded that the compressive strength of the Soil-Cement Block masonry prism decreases as the mortar bed joint thickness is increased and the reduction in compressive strength is about 16% for a fivefold increase in bed joint thickness from 6 to 30 mm. Rehman and Ueda [2] conducted experimental investigation and numerical modeling of peak shear stress of brick masonry mortar joint under compression. They concluded that the shear capacity of the joints rises with an increase in confining pressure acting normal to the joint with its relationship consistent with the Mohr-Coulomb failure envelope. Basak et. al. [3] recommended the use of bed joint thickness not less than 20 mm in construction of conventional masonry walls in order to maintain the contribution of brick in conjunction with mortar under load.

Codes of different countries have recommended the mortar joint thickness to vary from 6mm to 15mm. Some researchers have suggested it to be more than 20mm. The observations and recommendations in literature indicate that between the suggested lower bound and upper bound of mortar thickness, there will be an optimum value of mortar thickness for a given strength of mortar. This study presents assessment of In-plane and Out-of-plane behavior of a brick masonry wall subjected to inertial load equivalent to Design Basis Earthquake (DBE) and Maximum Considered Earthquake (MCE) in seismic Zone IV and Zone V. The parametric variation in thickness of mortar concludes optimized thickness for a given strength of mortar for an improved behavior of the wall.

Keywords: masonry; earthquake; mortar; brick; behavior

1. Introduction

Masonry is a composite material made of units, e.g., clay bricks or concrete blocks, and mortar. The strength of masonry depends on several factors and the thickness of the mortar joint & strength of mortar are the significant factors influencing masonry strength. IS 2212:1991 [4] suggests the preferred mortar thickness to be 12mm or less. The Australian Structural Masonry Code AS:3700 [5] and the Canadian Masonry Code S304-14 [6] provide an allowable range for horizontal joint thickness of (10 ± 3) mm. The Eurocode EN 1996-1-1 [7] indicates the range of 6 to 15 mm for the mortar joint thickness. Mortar joint thickness is an important component of lining system that has some effect in masonry units and mortar bond strength. As brick masonry is a composite material, the understanding of its in-plane and out of plane behavior is very much essential.

Sarangapani et al. [8] studied flexural bond strength and shear bond strength of masonry using different types of local bricks and mortars and concluded that an increase in bond strength, while keeping the mortar strength constant, leads to an increase in the compressive strength of masonry. Reddy et. al. [1] conducted tests on masonry prisms and studied the influence of joint thickness on compressive strength of soil-cement block masonry. It is found that the thickness of the joint affects not only the strength of masonry, but also the Young's modulus, the coefficient of transversal deformation and the nature of a failure in masonry. Also, the masonry compressive strength is sensitive to the ratio of modulus of block to that of the mortar which decreases with increase in mortar joint thickness if modular ratio is more than 1. The reduction in compressive strength is about 16% for a fivefold increase in bed joint thickness from 6 to 30 mm.

Rehman and Ueda [2] conducted experimental investigation of peak shear stress of brick masonry mortar joints of different thickness under compression. They concluded that the shear capacity of the joints rises with an increase in confining pressure acting normal to the joint with its relationship consistent with the Mohr-Coulomb failure envelope. Zavalis et al. [9] analyzed influence of bed joint thickness on modulus of elasticity of masonry and concluded that modulus of elasticity depends on the properties of mortar, masonry unit and bed joint thickness using an analytical model developed in the study.

Basak et al. [3] recommended the use of bed joint thickness not less than 20 mm in construction of conventional masonry walls in order to maintain the contribution of brick in conjunction with mortar under load. Zengin et al. [10] investigated the effect of joint thickness and also type of mortar on the mechanical behavior of the masonry walls. With three different joint thicknesses for each mortar type; a total of six masonry walls were tested in the laboratory. The study concludes that the failure mechanism of the brick masonry walls differed due to the mechanical properties of the mortars. The use of bed joint thickness not less than 20 mm is recommended in construction of conventional masonry walls in order to maintain the act of brick in conjunction with mortar under load. The lateral load capacities of the walls with a joint thickness of 10 mm and 30 mm were close to each other, but a larger scale of damage was observed in the walls with a joint thickness of 10 mm.

Hassan Ali et al. [11] investigated the effects of sandy clay into cement mortar on the bending strength of masonry unit made of clay brick, cement brick and lightweight brick. The thickness of the mortar joint was varied as 10mm, 20mm and 30mm. The study shows that masonry prism built with sandy clay mortar has higher bending strength compare to the fine sand mortar. The percentage increment in collapse load between 10mm thick mortar and 30mm thick mortar is 17.5% but not much increment is observed in 10 to 20mm thick mortar joint. Zengin et al. [12] in a study of effects of material type and joint thickness on conventional masonry walls concluded that a joint thickness of 20mm be preferred in wall construction due to more convenient compared to walls with thin (10mm) and thick (30 mm) joints. Also, the increase and decrease in the joint thickness affected the occurrence of damage.

Calderia et al. [13] studied the effects of joint thickness and strength of mortars on compressive strength of normal and high-strength concrete block masonry structure. The study concluded that the influence of joint thickness on structural behavior of masonry elements seems to be more significant when the mortar strength is much lower than the block strength. Also, joint thickness significantly affected the load-bearing capacity of masonry elements because increase of the joint thickness decreased the lateral confinement of the mortar and its strength.

Based on multiple suggestions given in published literature and also in codal provisions of different countries it is established that there is a need of research with respect to optimization of mortar joint thickness in masonry constructions, hence presented in this article.

2. Methodology

The gaps identified above have been addressed by analyzing walls with different mortar thickness of the same strength applied to the same size of walls. The in-plane stiffness of the wall is much higher than the out of plane stiffness and their failure patterns differs substantially. In order to study the effects of mortar thickness on behavior of walls infill wall and free standing wall of 3000x2700x110mm size have been considered. The mortar thicknesses considered are 5mm, 10mm, 15mm and 20mm. The size of brick has been considered as 230x70x50mm but other sized pieces have been used to achieve the same size of the wall. The top of the walls has a layer of mortar. The systems have been modeled using 8 noded solid brick finite elements, having 50mm mesh size, incorporated with a frictional interface between brick and mortar having coefficient of friction as 0.81 [14] using ABAQUS. The material properties considered are taken from literature [14, 15, 16] given in Table 1.

Table 1 – Material properties of brick and mortar

Sl. No.	Modulus of Elasticity (MPa)	Mass density ($N\text{-}s^2 / mm^4$)	Poisson's Ratio	Compressive strength (MPa)	Tensile Strength (MPa)
Brick	6095	2.0e-09	0.18	15.3	1.20
Mortar	3040	2.0e-09	0.20	7.3	0.78

The models have been subjected to inertial lateral loading corresponding to Design Basis Earthquake (DBE) and Maximum Credible Earthquake (MCE) for Zone-IV and Zone V applied in-plane and out-of-plane. The horizontal seismic coefficients A_h has been calculated using following equation suggested in IS1893:2016 [17]:

$$A_h = (Z/2) * (I/R) * S_a/g$$

Where, Z = 0.24 (Zone IV) and 0.36 (Zone V)
I = 1
R = 1.5 (for unreinforced load bearing masonry buildings)
S_a/g = 2.5 (Maximum value)

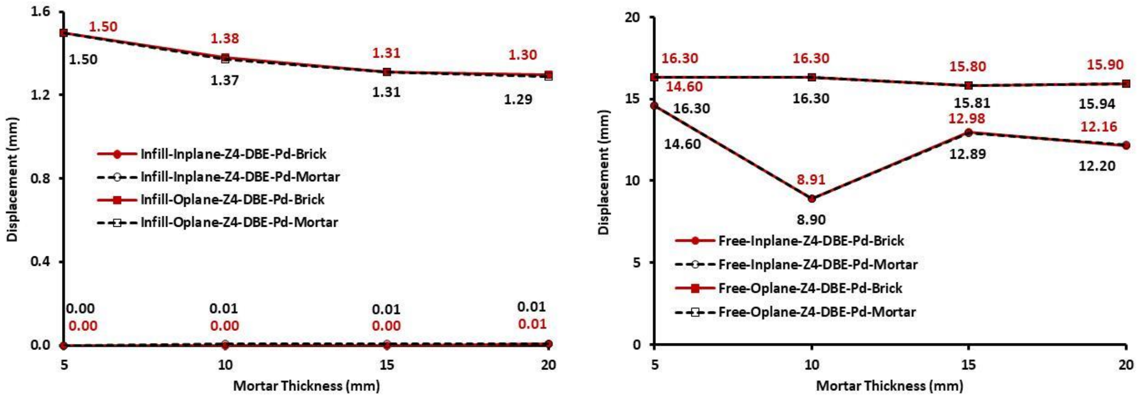
This calculates A_h as 0.20 and 0.40 for DBE and MCE respectively for Zone IV whereas 0.30 and 0.60 for Zone V. The boundary condition of both the walls is considered fixed at base but pinned on rest three sides in case of infill and free in case of free standing walls. The incrementally increasing inertial lateral load is applied and the response was calculated varying the acceleration @ interval of 0.05g until 0.60g with constant application of gravity load. The elastic response has been captured in terms of peak of displacements, maximum principal stress and minimum principal stress were noted occurring in bricks and mortar from the contours at DBE and MCE conditions for the mortar thickness of 5mm, 10mm, 15mm and 20mm.

3. Results and Discussions

The displacement response of In-fill wall subjected to in-plane and out-of-plane DBE loading on infill wall and free standing wall for seismic zone IV and seismic zone V have been presented in the form of graphs. The X-axis represents mortar thickness of 5mm, 10mm, 15mm and 20mm thicknesses. The Y-axis represents peaks of displacements (P_d) in mm, maximum principal stress (PS_{max}) and minimum principal stress (PS_{min}) in MPa.

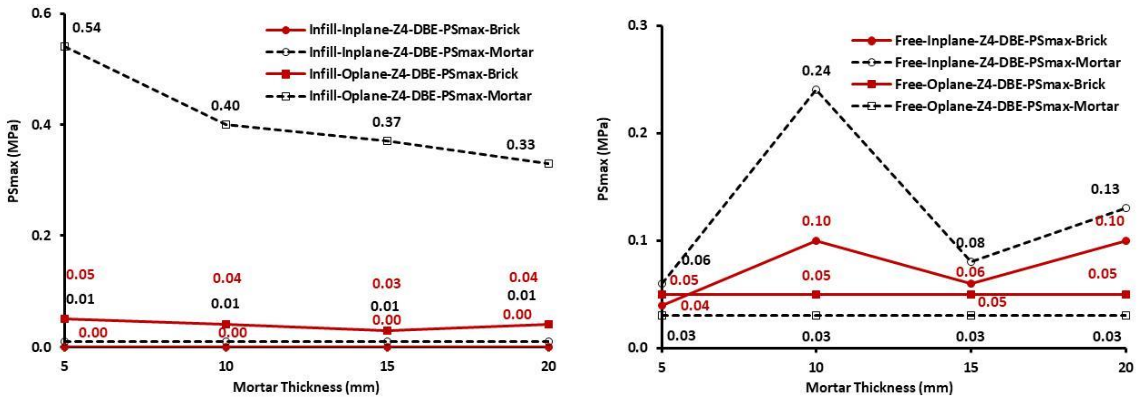
In case of infill wall subjected to Zone IV DBE loading (i) P_d is negligible in in-plane whereas maximum at 5mm & minimum at 20mm in out-of-plane (Fig.1a), (ii) PS_{max} is negligible in in-plane whereas maximum at 5mm & minimum at 20mm in out-of-plane (Fig.2a) and (iii) PS_{min} is nearly constant in in-plane for all thicknesses whereas maximum at 5mm & minimum at 20mm in out-of-plane (Fig.3a).

In case of free standing wall subjected to Zone IV DBE loading (i) P_d is minimum at 10mm in in-plane whereas maximum at 5mm & minimum at 20mm in out-of-plane (Fig.1b), (ii) PS_{max} is minimum at 5mm and maximum at 10mm in in-plane whereas nearly constant in out-of-plane (Fig.2b) and (iii) PS_{min} is minimum at 5mm and maximum at 10mm in in-plane whereas nearly constant in out-of-plane (Fig.3b).



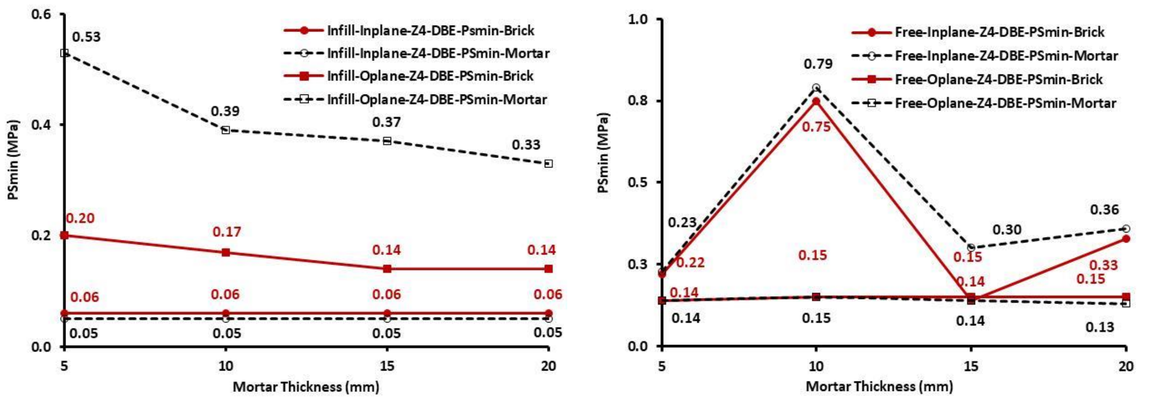
(a) Infill wall (b) Free standing wall

Fig. 1 - In-plane & out-of-plane peak displacement of infill & free standing wall in Zone IV DBE loading



(a) Infill wall (b) Free standing wall

Fig. 2 - In-plane & out-of-plane peak PS_{max} of infill & free standing wall in Zone IV DBE loading

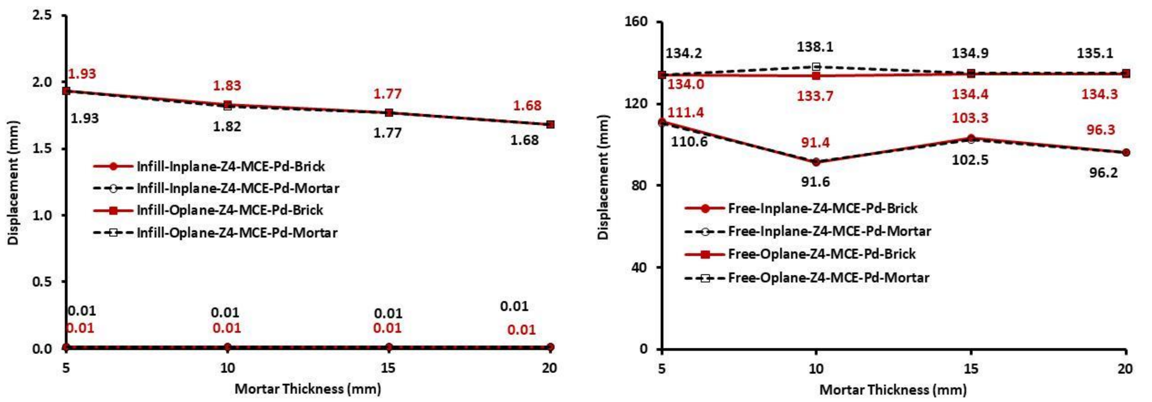


(a) Infill wall (b) Free standing wall

Fig. 3 - In-plane & out-of-plane peak PS_{min} of infill & free standing wall in Zone IV DBE loading

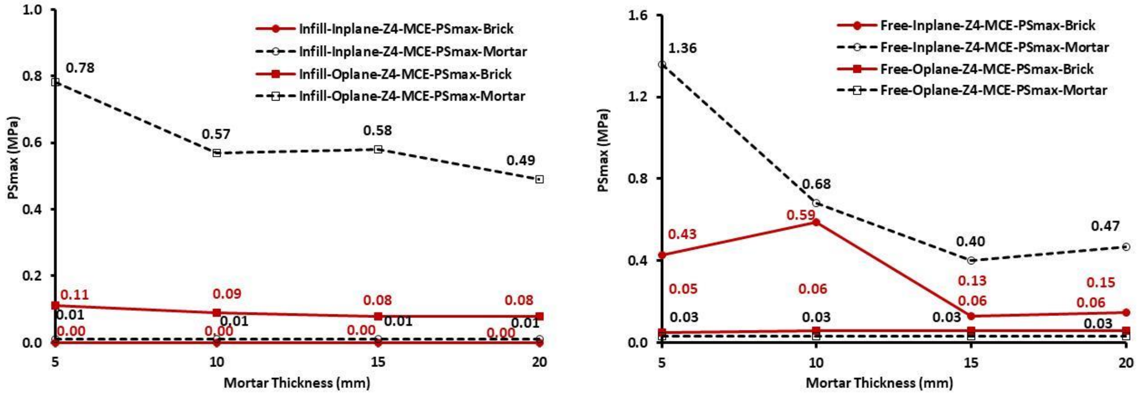
In case of infill wall subjected to Zone IV MCE loading (i) P_d is negligible in in-plane whereas minimum at 20mm & maximum at 5mm in out-of-plane (Fig.4a), (ii) PS_{max} is negligible in in-plane whereas minimum at 20mm & maximum at 5mm in out-of-plane (Fig.5a) and (iii) PS_{min} is nearly constant in in-plane for all thicknesses whereas minimum at 20mm & maximum at 5mm in out-of-plane (Fig.6a).

In case of free standing wall subjected to Zone IV MCE loading (i) P_d is minimum at 10mm in in-plane whereas minimum at 5mm & maximum at 10mm in out-of-plane (Fig.4b), (ii) PS_{max} is minimum at 15mm and maximum at 5mm in in-plane whereas nearly constant in out-of-plane (Fig.5b) and (iii) PS_{min} is minimum at 10mm and maximum at 20mm in in-plane whereas nearly constant in out-of-plane (Fig.6b).



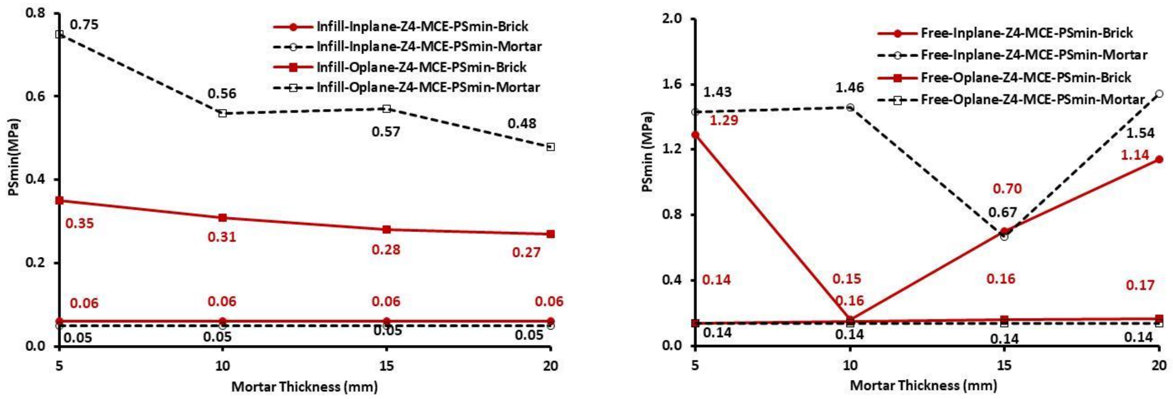
(a) Infill wall (b) Free standing wall

Fig. 4 - In-plane & out-of-plane peak displacement of infill & free standing wall in Zone IV MCE loading



(a) Infill wall (b) Free standing wall

Fig. 5 - In-plane & out-of-plane peak PS_{max} of infill & free standing wall in Zone IV MCE loading

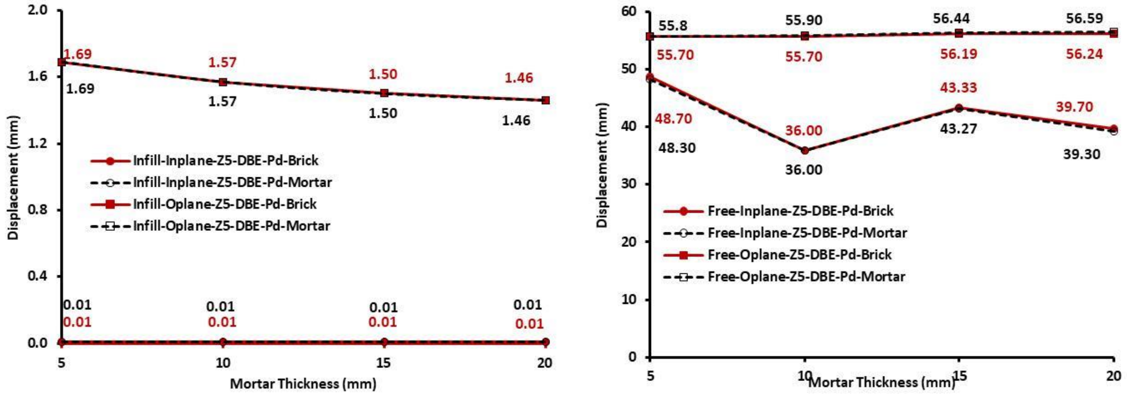


(a) Infill wall (b) Free standing wall

Fig. 6 - In-plane & out-of-plane peak PS_{min} of infill & free standing wall in Zone IV MCE loading

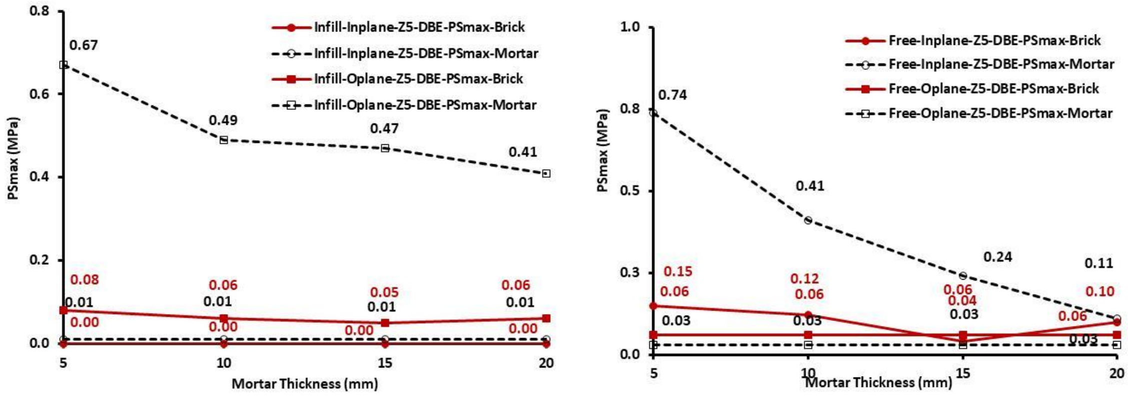
In case of infill wall subjected to Zone V DBE loading (i) P_d is negligible in in-plane whereas minimum at 20mm & maximum at 5mm in out-of-plane (Fig.7a), (ii) PS_{max} is negligible in in-plane whereas minimum at 20mm & maximum at 5mm in out-of-plane (Fig.8a) and (iii) PS_{min} is nearly constant in in-plane for all thicknesses whereas minimum at 20mm & maximum at 5mm in out-of-plane (Fig.9a).

In case of free standing wall subjected to Zone V DBE loading (i) P_d is minimum at 10mm in in-plane whereas minimum at 5mm & maximum at 20mm in out-of-plane (Fig.7b), (ii) PS_{max} is minimum at 20mm and maximum at 5mm in in-plane whereas nearly constant in out-of-plane (Fig.8b) and (iii) PS_{min} is minimum at 20mm and maximum at 10mm in in-plane whereas nearly constant in out-of-plane (Fig.9b).



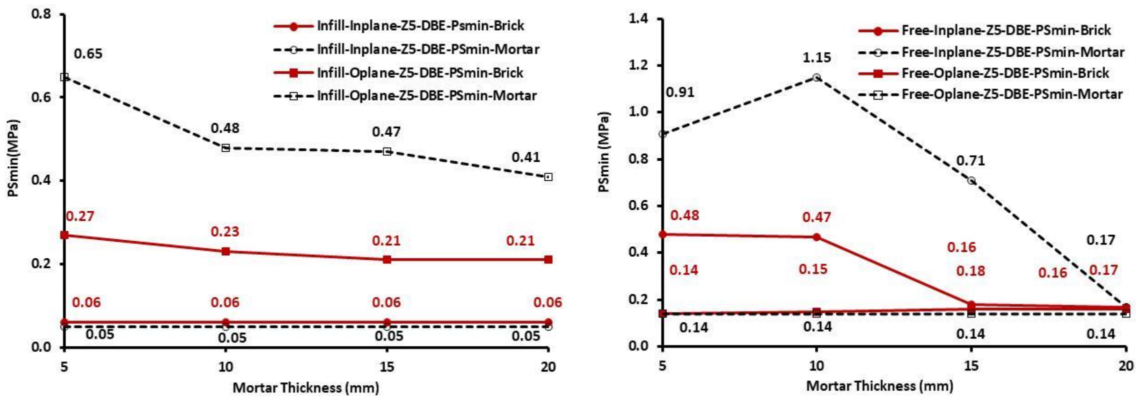
(a) Infill wall (b) Free standing wall

Fig. 7 - In-plane & out-of-plane peak displacement of infill & free standing wall in Zone V DBE loading



(a) Infill wall (b) Free standing wall

Fig. 8 - In-plane & out-of-plane peak PS_{max} of infill & free standing wall in Zone V DBE loading

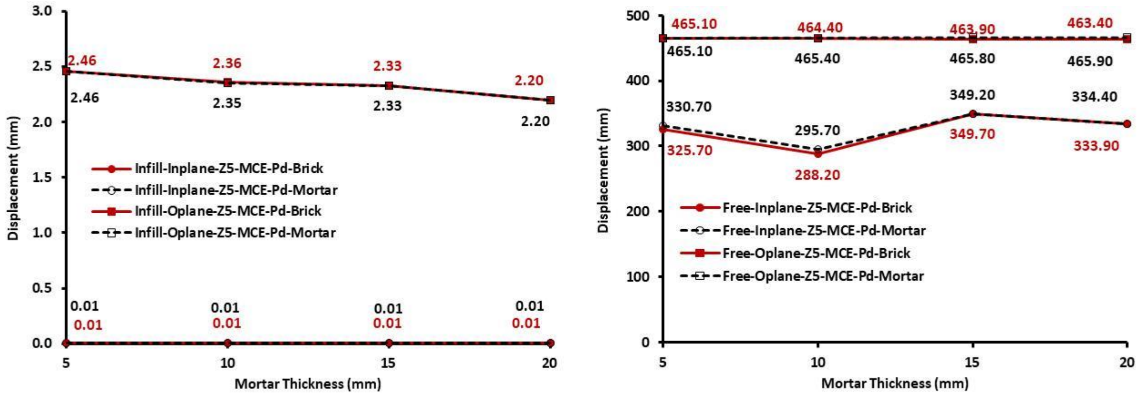


(a) Infill wall (b) Free standing wall

Fig. 9 - In-plane & out-of-plane peak PS_{min} of infill & free standing wall in Zone V DBE loading

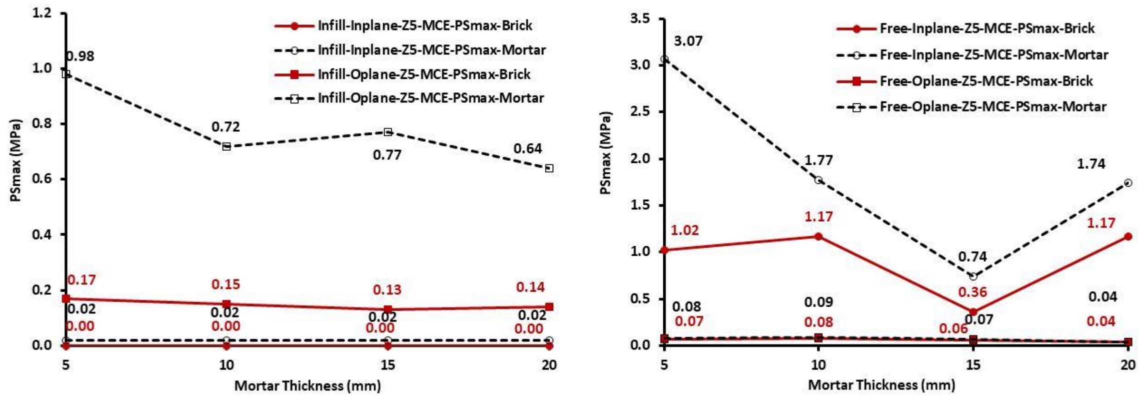
In case of infill wall subjected to Zone V MCE loading (i) P_d is negligible in in-plane whereas minimum at 15mm & maximum at 5mm in out-of-plane (Fig.10a), (ii) PS_{max} is negligible in in-plane whereas minimum at 20mm & maximum at 5mm in out-of-plane (Fig.11a) and (iii) PS_{min} is nearly constant in in-plane for all thicknesses whereas minimum at 20mm & maximum at 5mm in out-of-plane (Fig.12a).

In case of free standing wall subjected to Zone V MCE loading (i) P_d is minimum at 10mm and maximum at 15mm in in-plane whereas almost constant at all thicknesses in out-of-plane (Fig.10b), (ii) PS_{max} is minimum at 15mm and maximum at 5mm in in-plane whereas nearly constant in out-of-plane (Fig.11b) and (iii) PS_{min} is minimum at 15mm and maximum at 5mm in in-plane whereas nearly constant in out-of-plane (Fig.12b).



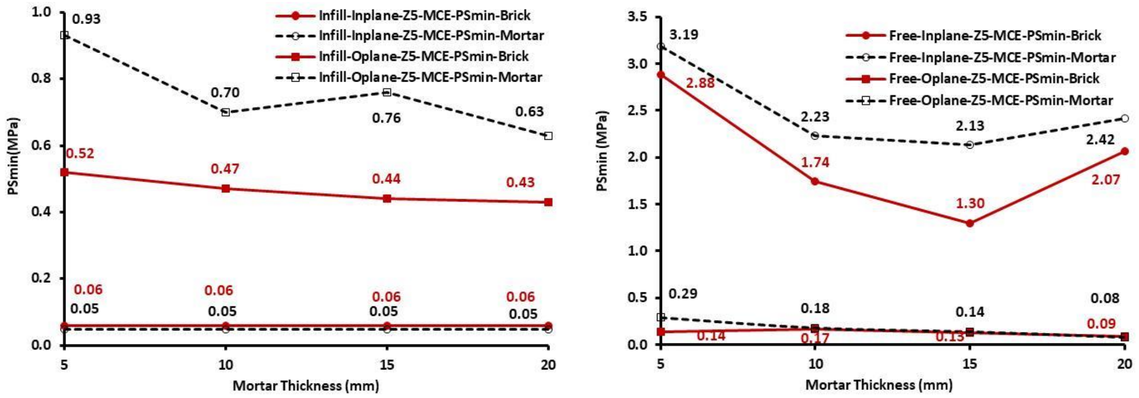
(b) Infill wall (b) Free standing wall

Fig. 10 - In-plane & out-of-plane peak displacement of infill & free standing wall in Zone V MCE loading



(a) Infill wall (b) Free standing wall

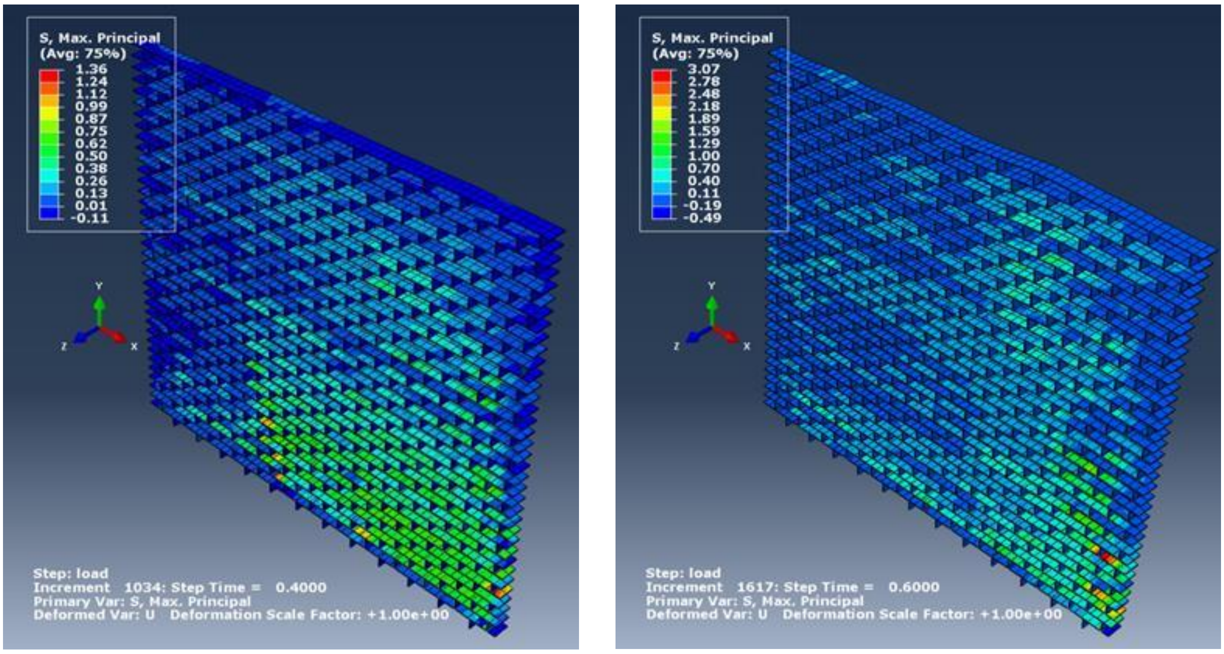
Fig. 11 - In-plane & out-of-plane peak PS_{max} of infill & free standing wall in Zone V MCE loading



(a) Infill wall (b) Free standing wall

Fig. 12 - In-plane & out-of-plane peak PS_{min} of infill & free standing wall in Zone V MCE loading

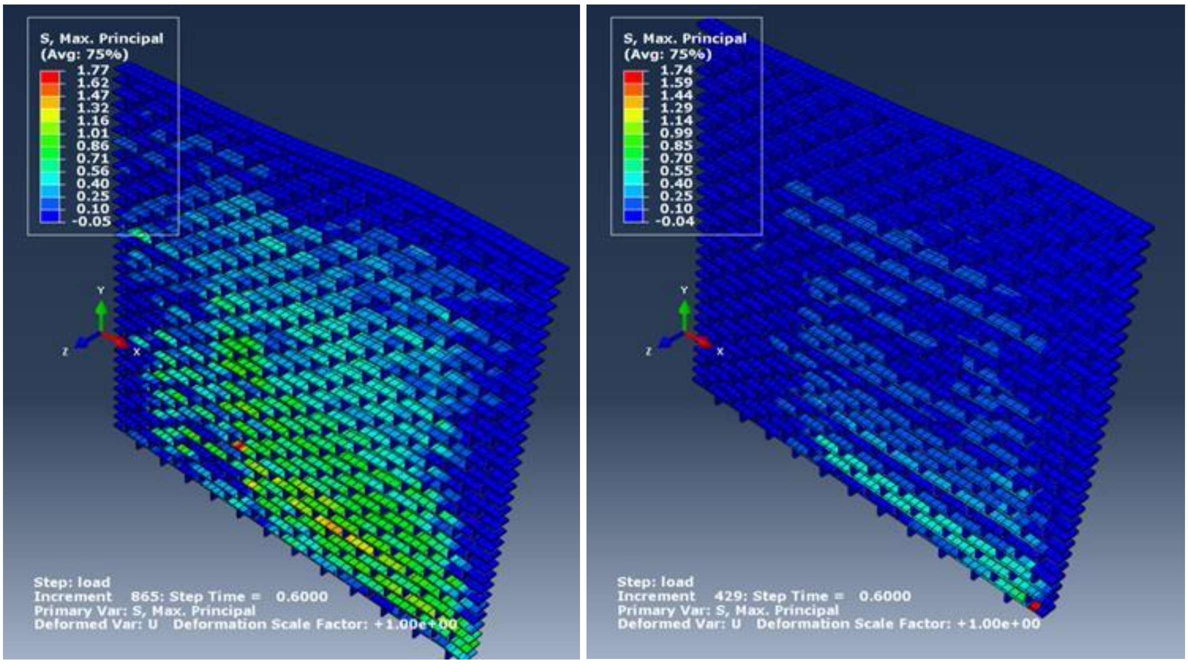
The results indicate that the stresses in mortar remain in permissible limits in all cases using 5 mm thick mortar except in case of MCE loading applied to (i) in-plane free standing wall in seismic Zone IV and seismic zone V causing peak tensile stress of 1.36 MPa and 3.07 MPa (Fig.13) respectively and (ii) out-of-plane infill wall in seismic Zone V causing peak tensile stress of 0.98 MPa all exceeding the permissible limit of 0.78 MPa.



(a) Seismic zone IV (b) Seismic zone V

Fig. 13 - In-plane PS_{max} contours in free standing wall with 5mm thickness of mortar at MCE

The results indicate that the stresses in mortar remain in permissible limits in all cases except in case of MCE loading applied to in-plane free standing wall in seismic Zone V causing peak tensile stress of 1.77 MPa and 1.74 MPa using 10mm and 20mm thick mortar respectively (Fig.14) all exceeding the permissible limit of 0.78 MPa.



(a) 10mm thick mortar (b) 20mm thick mortar

Fig. 14 - In-plane PS_{max} contours in free standing wall at MCE in Zone V

4. Conclusions

The study was carried out to capture in-plane and out-of-plane response of infill and free standing walls of size 3000x2700x110mm made of 230x110x70mm sized bricks joined with 5mm, 10mm, 15mm and 20mm thick mortar subjected to inertial lateral load corresponding to DBE and MCE in seismic Zone IV and Zone V. Following conclusions are drawn considering the principal stresses induced in the mortar and the bricks:

- The bricks do not get overstressed in all considered cases.
- The peak tensile stresses in mortar with mortar thickness of 5mm get exceeded in three cases by about 25%, 75% and 300% compared to the permissible limit of 0.78 MPa.
- The peak tensile stresses in mortar with mortar thickness of 10mm and 20mm get exceeded in one case each by about 125% compared to the permissible limit.
- The stresses in mortar remain in permissible limits in all cases using 15 mm thick mortar and hence can be considered as an optimized thickness providing best performance in terms of the induced stresses for the problem analyzed in this article.

5. Scope of future research

The present study considered the elastic behavior of the materials of bricks and mortar. The mortar was found stressed beyond its tensile strength hence material inelasticity needs to be considered. In addition, the parametric study with strength of mortar may be looked into.

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7. References

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