Effect of Grid Pattern on Load-Deformation Behavior of Paneled Masonry Walls

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SUMMARY:
Traditional masonry constructions (like *Dhajji-dewari* construction in Indian Himalayas) have shown satisfactory performance during recent earthquakes. In these structures a grid of horizontal, vertical and/or diagonal elements, divides a large wall into smaller wall areas and surrounding grid elements provide positive confinement to load-bearing masonry sub-panels. The effect of sub-paneling of wall using either vertical or horizontal or diagonal RC elements or their combinations was examined for approximately 50 different grid patterns using FE analysis. Confining masonry wall in smaller panels by grid elements helps in distributing inelastic activities throughout the wall panel and thereby substantially increasing its efficiency in resisting loads. The results of FE studies were used to develop simplified predictive relations for strength and stiffness values based on a confinement factor representing the grid element density. The proposed simple relations provide reasonable prediction of strength and stiffness and can be used to configure the grid elements for desired performance levels of sub-paneled masonry walls.

Keywords: Sub-paneled masonry wall, Finite Element Modeling, Traditional Masonry Construction

1. INTRODUCTION

One of the most common traditional methods of construction for earthquake-resistance is timber-brick masonry construction, which consists of burnt clay bricks filled in a framework of timber to create a patchwork of masonry, which is confined in small panels by the surrounding timber elements. Such building typologies are most commonly used for dwelling construction in certain parts of Indian subcontinent and in many Latin American countries. It is referred as *Dhajji-dewari* in India, *Colombage* in France and *Bahareque* in Central America. All these have shown acceptable performance during past earthquakes (Langenbach, 2003; Rai and Murty, 2006) (Fig. 1.1).

The basic feature of this timber frame with masonry infill construction is the placement of masonry in between a grid formed by vertical, horizontal and diagonal elements to form a complete timber truss frame. The presence of timber grid elements, which subdivide the infill, arrest the loss of a portion or complete masonry panels and resists progressive damage by distributing cracks (inelastic activity) throughout the wall panels. These types of structures resist lateral loads by allowing working along the interface of masonry and grid elements, which is the key to the energy dissipation capacity of the system. The closely-spaced studs prevent propagation of diagonal shear cracks within any large panel, and reduce the possibility of the out-of-plane failure of masonry (Gülkan and Langenbach, 2004).

Even though commonly recognized as an effective practice and traditionally adopted in various places, such building typologies are surprisingly not yet adequately supported by strong research. Little effort has yet been made to predict the behavioral aspects of such walls (Komaraneni et al., 2011; Ali et al., 2010). Also, the use of material other than timber, such as reinforced concrete (RC) members, for confining elements deserves further investigation for wider application. The objective of this paper is to study the effect of various grid patterns (confinement schemes) using RC elements on the in-plane behavior of sub-paneled masonry walls. It includes (*a*) analytical investigation of selected confinement schemes using RC members as grid elements through finite element (FE) analysis, and (*b*) developing a correlation among different design parameters related to strength, stiffness and length of confining grid elements using the analytical results.

(a) (b)

Figure 1.1 Traditional masonry for proven earthquake resistance: A system of timber laced masonry for confining masonry in small panels (Left photo source: www.e-architect.co.uk/haiti/haiti_buildings)

2. FINITE ELEMENT MODELING OF SUB-PANELED MASONRY WALLS

A two dimensional model in the state of plane stress was considered for both masonry panels and confining grid members. A finite element model was developed for sub-paneled masonry walls with approximately 50 different grid patterns using the general purpose program Abaqus (Simulia, 2010). The masonry was modeled at the macroscopic level, however the interaction between the masonry and its confinement was done at the microscopic level. The concrete damaged plasticity model in Abaqus was used to simulate the inelastic behavior of masonry and confining RC grid members. The model uses the concepts of isotropic damaged elasticity in combination with isotropic tensile and compressive plasticity to represent the inelastic behavior.

2.1. Material Properties

The material properties used were obtained primarily from the laboratory tests conducted by Mukherjee (2006). The stress-strain curve specified for masonry in compression was developed using simplified tri-linear model proposed by Kaushik et al. (2007) as shown in Fig. 2.1a. For tensile behavior, it was assumed that the peak tensile strength of 0.35 MPa would be reached at a strain of 0.0001 (Dhanasekar, 2008). The post peak behavior is approximated by a straight line up to the strain value of 0.001 and minimum stress of 0.1 MPa as shown in Fig. 2.1a. These values are selected to provide smooth strength degradation needed for convergence of Abaqus solution procedure. The model proposed by Kent and Park (1971) was used in describing the compressive behavior of concrete (Fig. 2.1b). The tensile strength of concrete was taken as $0.7\sqrt{f_{ck}}$ = 3.8 MPa (compressive strength of concrete cylinder, f_{ck} = 30 MPa) to develop stress-strain curve shown in Fig. 2.1b. The properties of concrete and masonry used for the analysis are mentioned in Table 2.1. Other required material properties for concrete damaged plasticity model are taken as: dilation angle = 30°, flow potential eccentricity = 0.1, ratio of initial equi-biaxial compressive yield stress to initial uniaxial compressive yield stress = 1.16, ratio of second stress invariant = 0.667, viscosity parameter = $1\times10^{-5}$and 0.003 for masonry and concrete, respectively.

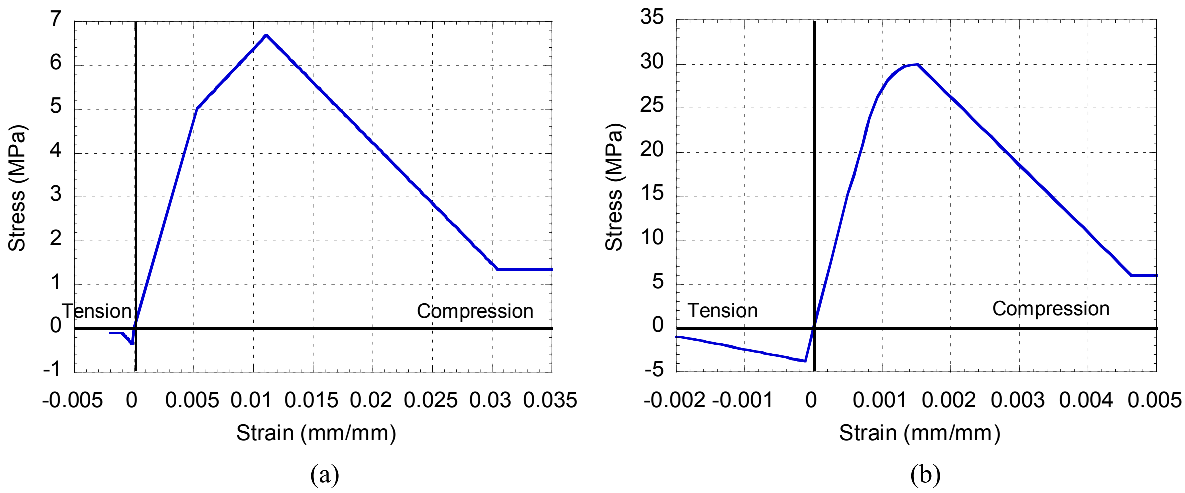


Figure 2.1 Stress-strain curve used for finite element modeling (a) masonry and (b) concrete

Table 2.1 Properties of masonry and concrete used in finite element modeling

Sr. No.	Properties	Masonry	Concrete
1.	Density (kg/m^3)	1900	2400
2.	Young's Modulus (GPa)	0.95	30
3.	Poisson's ratio	0.2	0.2
4.	Compressive Strength (MPa)	6.69	30
5.	Tensile Strength (MPa)	0.35	3.8

2.2. Model Details

The prototype sub-assembly considered was a masonry wall having dimensions of 5 m × 3 m ($l \times h$), typical in masonry buildings for schools and dwellings. All sub-paneling schemes had 100 mm thick walls and were provided with confining frames made with RC elements. These RC grid elements had cross sections of 100 mm × 100 mm (width × thickness). The discretization of masonry and grid members of confining schemes with diagonal member was achieved by three-noded linear plane stress elements (CPS3) of the Abaqus element library (Simulia, 2010). Four-noded bilinear quadrilateral elements (CPS4R) were used to model the vertical and horizontal confining grid members for schemes without diagonal grid element. The monolithic connections were assumed between RC grid elements and were suitably emulated in the FE model.

Appropriate description through *Surface Interaction* (surface-to-surface contact) was assigned both in the tangential direction and normal direction in order to account for the possible slip phenomena at the interface of masonry and grid elements. The penalty based contact was used in tangential direction with coefficient of friction, $\mu = 0.6$ and hard contact was specified in normal direction which can only transmit the contact pressure when surfaces are in contact with each other. A schematic diagram of a typical wall representing the different finite elements is shown in Fig. 2.2.

The appropriate boundary conditions were achieved by either deleting or constraining relevant nodal degrees of freedom of various elements. All the degrees of freedom of the nodes at the base were restrained in order to simulate a fixed boundary condition. The interaction at edges/boundaries of the masonry and confining grid elements were defined appropriately to allow desired energy dissipation due to friction at their interface.

The models were first subjected to a constant vertical pressure of 0.1 MPa to represent loads from the upper floors, and then lateral displacements were applied. The FE models were subjected to a monotonically increasing load and this simplified scheme of analysis is capable of providing essential load-deformation behavior of the sub-paneled masonry walls. A limitation of this FE modeling is that it is incapable of handling the strength and stiffness degradation associated with reverse cyclic loading, which is associated with typical earthquake ground motions.

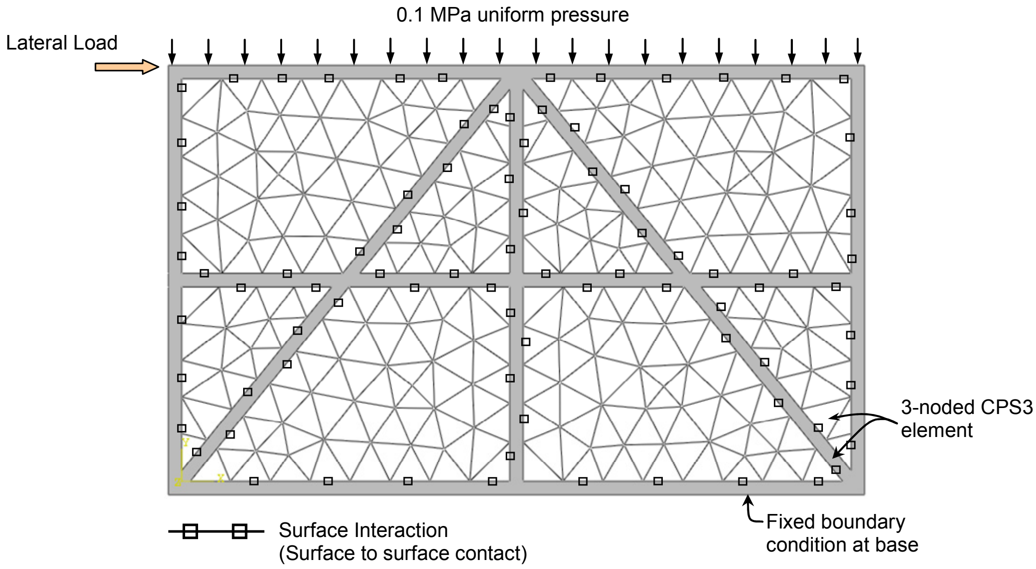


Figure 2.2 Schematic diagram of a typical FE model of sub-paneled wall used in the analysis

3. TREND FOR STRENGTH AND STIFFNESS

The performance of a masonry wall under earthquake loading can be stated in terms of its load carrying capacity (strength), stiffness, ductility or their combination which determines the energy dissipation potential of the system. Among these three parameters, strength and stiffness have been considered as *performance parameters* in the present study. *Geometric parameters* were introduced to quantify the degree of confinement (sub-paneling). The length of confining grid elements, the aspect ratio of the largest masonry panel, the volume of confining elements etc., can be considered as geometric parameters. The length of confining grid elements was chosen to define the geometric parameter for this study.

3.1. Confinement Factor

The term *confinement factor* was introduced to indicate the degree of confinement provided in masonry panel by internal grid element. The *confinement factor* is defined as a ratio of total length of internal grid elements, i_t to the length of confining elements at the perimeter of the wall, t. For example, for confining scheme shown in Fig. 2.2, the length of internal grid elements (vertical, i_v = 3.0 m; horizontal, i_h = 5.0 m and two diagonals, i_d = 7.8 m), i.e. i_t = 15.8 m and the confining elements at the perimeter, t = 16.0 m, therefore, the confinement factor, $i_t / t \approx 1.0$.

3.2. Results and Discussion

The ultimate shear resistance or strength, R_u of the wall is defined as the peak load carrying capacity of the masonry wall. The strength (R_u) is designated as R_c and R_{nc} for masonry walls with and without confining grid elements, respectively. The ratio R_c / R_{nc} is defined as the strength factor, a factor which signifies the relative increase in the capacity of a sub-paneled wall as compared to an unconfined masonry wall. Similarly, a stiffness factor, K_c / K_{nc} is defined where, K_c and K_{nc} denote effective stiffness for a wall with and without confining (sub-paneling) grid elements, respectively. The in-plane shear strength and stiffness of unconfined masonry walls were calculated as 60 kN and 40 kN/m using the recommendation of IITK-GSDMA Guidelines (2007) and FEMA 356 (2000), respectively.

The effective stiffness was estimated by idealizing the load-deformation plot with a bi-linear curve as shown in Fig. 3.1. The elastic stiffness, K_c and yield strength, R_y should be such that the resulting area under the bilinear curve is equivalent to the 'actual curve'. A possible choice of elastic stiffness is the secant stiffness at 0.75 R_y (Magenes and Calvi, 1997). Studies performed by Tomazevic (1996) have shown that assuming $R_y = 0.9\,R_u$ (ultimate load resistance) is appropriate value for 'energy equivalence' (i.e., area A = area B in Fig. 3.1) in masonry walls and the corresponding displacement can be defined as yield displacement, δ_y. Thus, elastic stiffness can be approximated as secant stiffness at 0.6 R_u. A value of $\lambda = 0.1$ is taken for the ratio of post-yield (degraded) stiffness to the elastic stiffness (Reinhorn et al., 1995). Using analytical results, R_c / R_{nc} and K_c / K_{nc} were evaluated for various confinement schemes and plotted against their respective i_t / t ratios as shown from Figs. 3.2a to 3.2e.

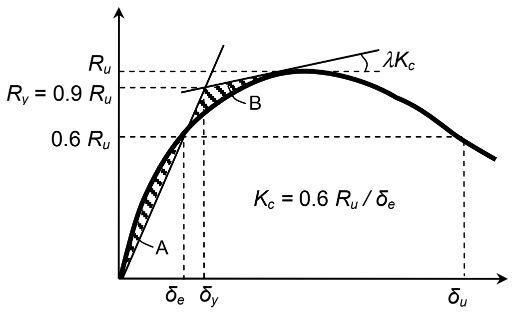


Figure 3.1 Schematic representation showing the different behavioral quantities of the analytical load-displacement curve

3.2.1. Effect of Grid Configuration

The effect of sub-paneling of wall using either vertical or horizontal or diagonal RC elements was first examined and subsequently, combinations of these elements were studied for approximately 50 different grid patterns. The effect of grid configurations on behavior of masonry panel in terms of strength and stiffness factor is shown in Figs. 3.2a to 3.2e and also stress distribution in masonry panels for selected schemes is presented through contour diagrams in these figures. As illustrated from stress contours in Fig. 3.2a, the inclusion of vertical grid elements cause the formation of multiple diagonal struts i.e., strut in each sub-panels. Thus it resulted in higher strength of masonry wall as compared to the unconfined wall. However, with the increase in number of vertical grid elements the strength and stiffness reduces due to the lower aspect ratio (length/height) of panel ("narrowness") which results in reduced width of diagonal strut.

The addition of horizontal grid elements produced pre-defined slippage planes and led to insignificant improvement in strength and much lower stiffness as compared to the basic model (i_t / t = 0.31) as well as unconfined masonry wall as shown in Fig. 3.2b. Moreover, the stress contours exemplify that horizontal grid element hinders the formation of diagonal strut. However, the presence of such pre-defined slippage plane may further facilitate energy dissipation thereby augmenting the deformability/ductility of the wall as also observed by Paikara and Rai (2006) and Mukherjee (2006).

Inclusion of diagonal elements considerably enhances the strength and stiffness of sub-paneled masonry wall (Fig. 3.2c). This can be expected as the diagonal elements offered stiffer and more direct paths for the transfer of the stresses to the fixed base. This mechanism is similar to that of truss or a frame wherein the diagonal or oblique elements transfer forces directly to the joints. As observed from the stress contours of confinement schemes (i_t / t = 0.49 and 0.98) in Fig. 3.2c, that the diagonal elements relieve and distribute the stresses in masonry along and perpendicular to its plane. Therefore, it results in much better use of masonry sub-panels until the forces in diagonal member do not cause failure or crushing at the corners, where comparatively higher stresses are generated.

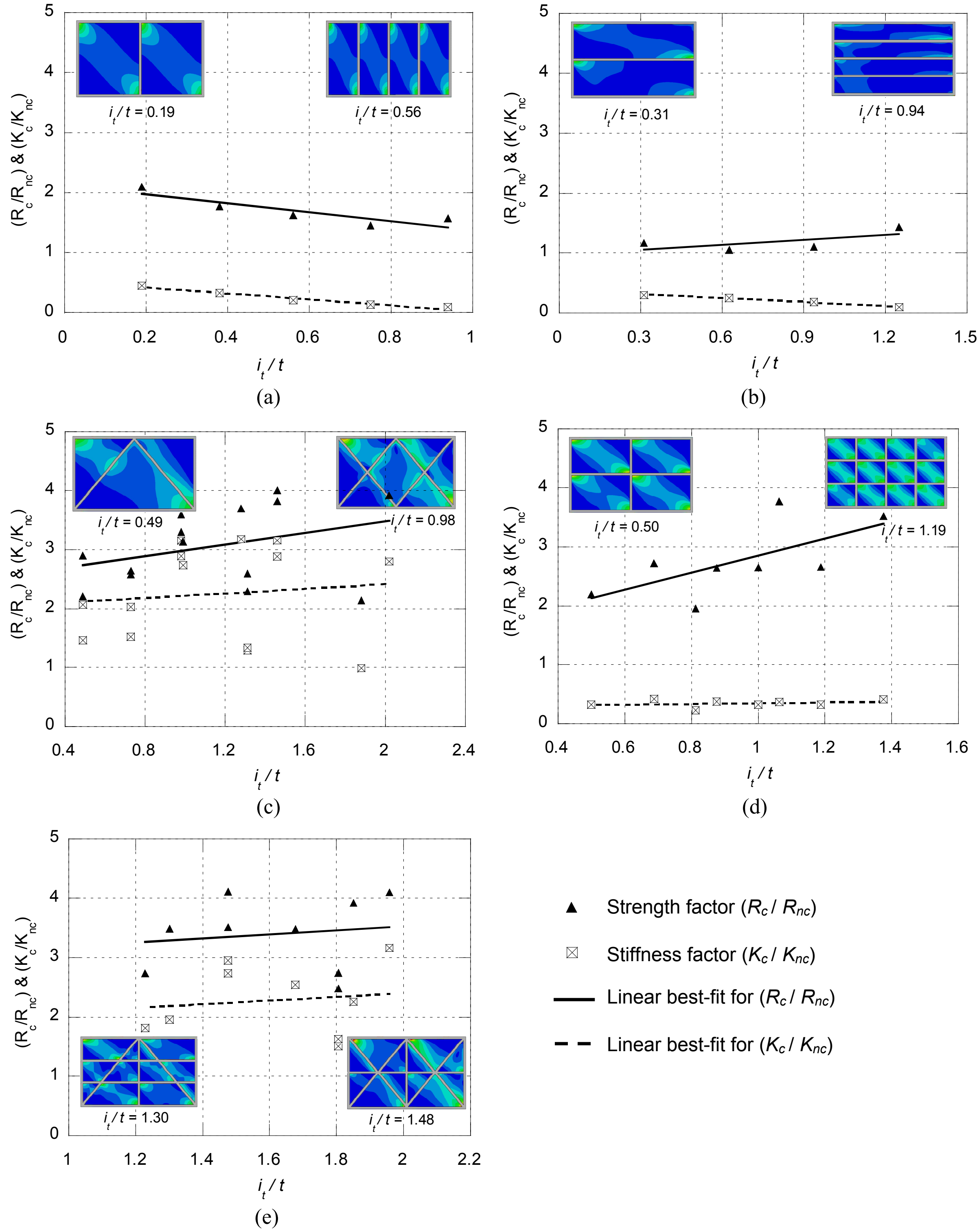


Figure 3.2 Trend for strength and stiffness (linear best fit of analytical results) for confinement schemes with (a) only vertical grid elements, (b) only horizontal grid elements, (c) only diagonal grid elements, (d) combination of vertical and horizontal grid elements, and (e) all three types of grid elements.

Furthermore, finite element models were developed to evaluate the effect of combination of either any two or all grid element types on behavior of masonry walls. It can be observed from Fig. 3.2d that inclusion of both vertical and horizontal confining element for sub-paneling results in highly efficient use of the masonry as a lateral load resisting element by developing diagonal struts in each panel. When all three elements were used in combination for sub-paneling, it helped in distributing lateral loads in wall panels thereby substantially increasing its efficiency in resisting loads. For instance, sub-paneling a masonry wall into twelve panels (i_t / t = 1.30, Fig. 3.2e) using horizontal, vertical and diagonal grid elements improved its strength and stiffness by 2.7 and 1.8 times, respectively. Moreover, the orientation and position of the confining elements plays a crucial role in determining the behavior of sub-paneled masonry wall; as shown in Fig. 3.2e, the schemes with same confinement factor (i_t / t) had significant difference in their observed strength and stiffness.

4. DEVELOPMENT OF SIMPLIFIED PREDICTIVE EQUATION

The observed values of R_c / R_{nc} and K_c / K_{nc} for various confinement schemes are plotted against their respective i_t / t ratios as shown in Figs. 4.1a and 4.1b, respectively. Using regression analysis a linear best-fit model was proposed to predict the strength and stiffness (Figs. 4.1a and 4.1b). However, the accuracy of the model was highly unreliable due to poor regression coefficient of about 0.2 and thus improved relation is needed to predict the strength and stiffness of sub-paneled masonry walls.

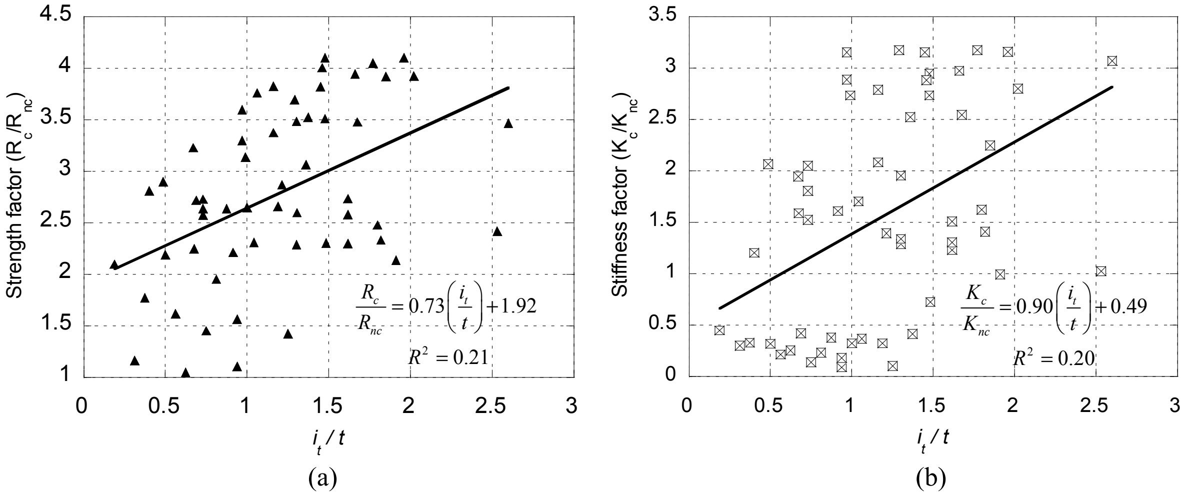


Figure 4.1 Trend for (a) strength and (b) stiffness (linear best fit of analytical results) for all confinement schemes

Previous discussion highlighted the varying contributions of horizontal, vertical and diagonal elements in determining the overall confining effect and behavior of sub-paneled masonry walls. Therefore, to being with, an empirical relation was developed to predict strength and stiffness of sub-paneled masonry with only a particular grid element type, i.e., either vertical or horizontal or diagonal element. As shown in Figs. 3.2a and 3.2b, strength and stiffness of masonry wall with either vertical or horizontal grid element can be predicted accurately using linear best-fit relation (Eqns. 1a to 2b as shown in Table 4.1). However, as indicated from Fig. 3.2c, the performance parameters for masonry walls with only diagonal grid element shows poor correlation with i_t / t, but by resolving the length of diagonal grid elements into horizontal (d_h) and vertical (d_v) components considering their distinct roles, the strength and stiffness can be predicted closely using proposed relation in Eqns. 3a and 3b (regression coefficient ≈ 0.70). In Table 4.1, F and K denote strength factor (R_c / R_{nc}) and stiffness factor (K_c / K_{nc}), respectively and the subscript v, h and d indicate the type of grid element (vertical, horizontal and diagonal) used in confining scheme.

Secondly, the strength and stiffness response of sub-paneling schemes with combination of any two or all three types of confining elements is considered as a function of masonry panels with each type grid elements and number of sub-panels, N in a parent confining scheme. Thus, using the above method another set of linear regression analysis was carried to derive the relations for predicting the strength and stiffness of confinement schemes consisting of grid element types *i*) vertical and horizontal, *ii*) vertical and diagonal, *iii*) horizontal and diagonal, and *iv*) vertical, horizontal and diagonal. All these relations are listed in Table 4.1 (Eqns. 4a to 7b) and can be used to estimate the strength and stiffness for confining schemes with various combinations of grid element types. For example, to estimate the strength factor for confining scheme shown in Fig. 2.2 (t = 16.0 m), calculate F_v, F_h and F_d for i_v = 3.0 m, i_h = 5.0 m, d_v = 6.0 m and d_h = 5.0 m using Eqns. 1a to 3a, respectively. Substitute these values and number of panels, N =8 in Eqn. 7a to estimate the strength factor $(R_c/R_{nc})_{hvd}$ = 2.70.

The strength and stiffness for sub-paneling schemes with more than two types of grid elements were predicted using proposed relations and compared with results of FE analysis as shown in Fig. 4.2. Considering the significant disparity in response of sub-panel masonry walls, specially with diagonal elements (Figs. 3.2e and 4.1), the proposed relation satisfactorily predicts the strength and stiffness (error < 25%) for various confining schemes.

Table 4.1 Predictor relation for strength and stiffness of masonry panel with different grid patterns (sub-paneling schemes)

Sub-paneling Scheme	Strength factor (R_c/R_{nc})	Stiffness factor (K_c/K_{nc})
Only vertical	$F_v = -0.74\left(\frac{i_v}{t}\right) + 2.11$ (1a)	$K_v = -0.48\left(\frac{i_v}{t}\right) + 0.51$ (1b)
Only horizontal	$F_h = 0.27\left(\frac{i_h}{t}\right) + 0.98$ (2a)	$K_h = -0.22\left(\frac{i_h}{t}\right) + 0.38$ (2b)
Only diagonal	$F_d = 2.23\left(\frac{d_v}{t}\right) + 0.08\left(\frac{d_h}{t}\right) + 1.73$ (3a)	$K_d = 2.71\left(\frac{d_v}{t}\right) - 0.32\left(\frac{d_h}{t}\right) + 1.02$ (3b)
Vertical and horizontal	$F_{hv} = -1.96F_h - 3.23F_v + 0.01N + 10.54$ (4a)	$K_{hv} = 3.02K_h + 0.86K_v + 0.03N - 1.12$ (4b)
Vertical and diagonal	$F_{vd} = 3.24F_v + 2.35F_d - 0.22N - 8.91$ (5a)	$K_{vd} = -1.65K_v + 0.23K_d + 0.07N + 1.75$ (5b)
Horizontal and diagonal	$F_{hd} = -4.66F_h - 0.36F_d + 0.13N + 7.24$ (6a)	$K_{hd} = -3.42K_h + 1.98K_d - 0.01N - 0.88$ (6a)
Vertical, horizontal and diagonal	$F_{hvd} = 8.28F_h - 1.01F_v + 1.05F_d + 0.04N - 7.13$ (7a)	$K_{hvd} = 1.89K_h + 2.46K_v + 0.73K_d + 0.06N - 1.75$ (7b)

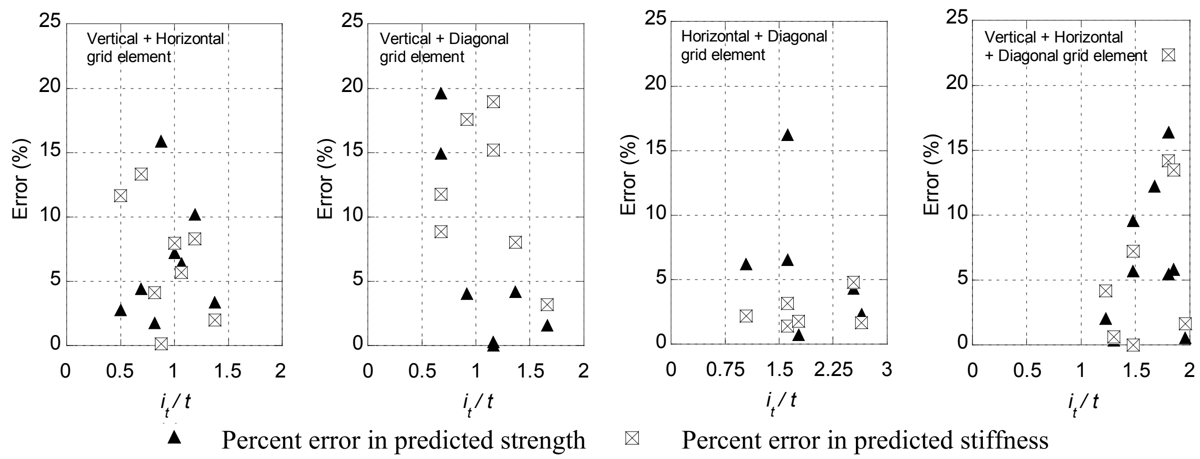
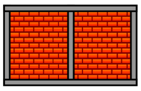
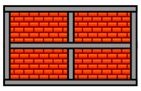
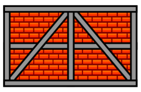
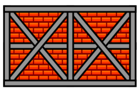


Figure 4.2 Percent error in prediction of strength and stiffness using proposed relations in comparison to FE results of sub-paneled masonry wall with a) vertical and horizontal, b) Vertical and diagonal, c) Horizontal and diagonal, and d) Vertical, horizontal and diagonal grid elements.

4.1. Comparison with Experimental Results

Paikara and Rai (2006) and Mukherjee (2006) conducted pseudo-static cyclic tests on half-scaled wall specimens ($l = 2.5$ m and $h = 1.5$ m) with different sub-paneling schemes using RC pre-cast grid elements. The strength and effective stiffness values observed from FE analysis and predicted using proposed relations for laboratory examined sub-paneling schemes are compared with experimental results as shown in Table 4.2. The predicted strength values were found to be in good agreement with the experimental values. However, the stiffness values are only reasonably predicted for confining schemes with no diagonal grid element. The large discrepancy in stiffness values for schemes with diagonal element is primarily due to inadequate modeling of connection among various grid elements. In the FE analysis, more stiffer monolithic connection was assumed, while experimentally investigated sub-paneling schemes utilized rather flexible connections of joining grid elements with metal straps. The simplified geometric parameters i_h, i_v and i_d provide an acceptable basis for describing strength and stiffness of sub-paneled masonry walls, which are rather complex functions of grid configuration, boundary conditions, connections, and the interplay of masonry blocks and grid elements. These geometric parameters can be used to determine the storey stiffness and strength of sub-paneled walls which can be used to predict the global behavior of the structure.

Table 4.2 Comparison of strength and stiffness factors as obtained from the experiment, FE model and regression analysis.

Confinement Scheme	Strength factor (R_c / R_{nc})			Stiffness factor (K_c / K_{nc})		
	Exp.§	FE Model	Predictive relation	Exp.	FE Model	Predictive relation
	1.25	2.10 [0.60]*	1.98 [0.63]	0.48	0.44 [1.09]	0.42 [1.14]
	1.62	2.19 [0.74]	2.09 [0.78]	0.37	0.31 [1.19]	0.30 [1.23]
	2.96	3.26 [0.91]	2.73 [1.08]	0.55	1.54 [0.36]	1.76 [0.31]
	2.42	4.10 [0.60]	3.79 [0.64]	0.34	2.95 [0.12]	2.67 [0.13]

§ strength and stiffness values for laboratory examined confined schemes were normalized with corresponding values for unconfined masonry wall.
* the values in the [ ] show the ratio of experimental value to that obtained from FE model or regression analysis.

5. CONCLUSIONS

The present study concerns the improved in-plane resistance of URM walls by the use of confining grid elements. The proposed system of confining the masonry walls/panels can be used as an improvement for 2-3 storey unreinforced masonry houses. In addition, the various proposed confining schemes can be employed for enhancing the in-plane and out-of-plane capacity of masonry infill in multi-storey RC frame buildings. Analytical investigations clearly indicate that sub-paneling the masonry wall with grid elements enhances lateral capacity of the walls. Their placement and spacing greatly influences the behavior of the system as a whole.

The strength and stiffness of sub-paneled masonry walls of different grid patterns were correlated by means of a confinement factor (i_t / t) and considering the distinct role of various element types forming the sub-panels, such as, vertical, horizontal and diagonal elements, simple predictive relations were derived from analytical results. These relations provide reasonable estimate of response (strength and stiffness) of sub-paneled masonry walls as it accounts for contribution of each element type separately through their individual confinement factors. However, further improvement in the FE model is required with respect to adequate simulation of the connection details, strength and stiffness degradation. The proposed design parameters can be used to formulate guidelines for sub-paneled masonry walls for new constructions as well as replacements walls in existing structures for satisfactory seismic performance.

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