EARTHQUAKE RESISTANT DESIGN OF MASONRY BUILDINGS

Introduction

Masonry construction is the oldest and most common building technique, together with timber construction. The word “masonry” actually encompasses techniques which may differ substantially depending on type and shape of materials and construction methods. In general, masonry may be defined as a structural assemblage of masonry units (such as stones, bricks and blocks) with a binding material known as mortar. A vertical two-dimensional structure of such an assemblage is known as masonry wall. The walls of a masonry building and the building itself are designed to be stable, strong and durable to withstand a combination of design loads.

The basic advantage of masonry construction is that it is possible to use the same element to perform a variety of functions, which in a framed building, for example, have to be provided for separately, with consequent complication in detailed construction. Thus masonry may, simultaneously, provide structure, subdivision of space, thermal and acoustic insulation as well as fire and weather protection. As a material, it is relatively economical, durable and produces external wall finishes of acceptable appearance. Masonry construction is flexible in terms of building layout and can be constructed without very large capital expenditure on the part of the builder.

In India, at present, IS-1905 (1987, reaffirmed 1998) is the code of practice for “Structural Use of Un-reinforced Masonry”. A detailed hand book on Masonry Design and Construction is published by Bureau of Indian Standards in the form of SP-20 (S&T, 1991). An IS code for Structural Use of Reinforced Masonry is under preparation.

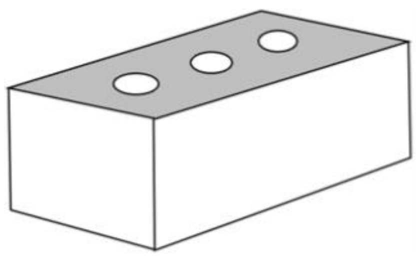
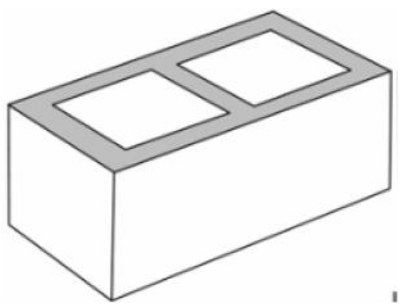
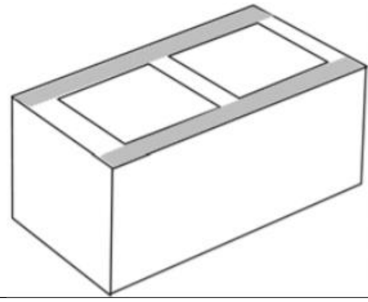
There are some guidelines for construction of reinforced masonry in IS-4326 (1993, reaffirmed 1998), mainly for earthquake resistant design and construction of masonry buildings. Guidelines for improving earthquake resistance of low-strength masonry buildings are covered separately in IS-13828 (1993, reaffirmed 1998).

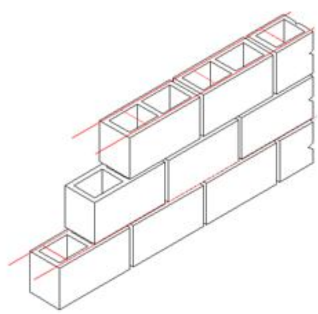
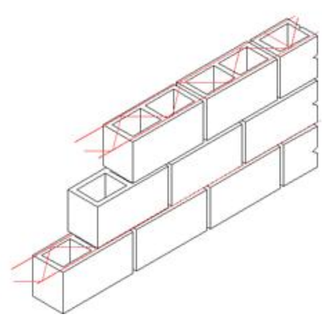
This chapter contains the following;

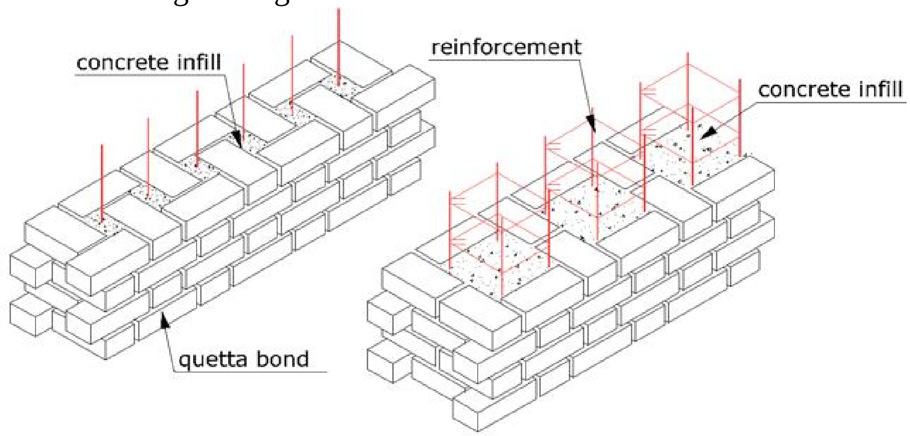
1. Terminologies in structural masonry
2. Basics of design of load bearing masonry
3. Concepts for reinforced masonry and earthquake resistant masonry

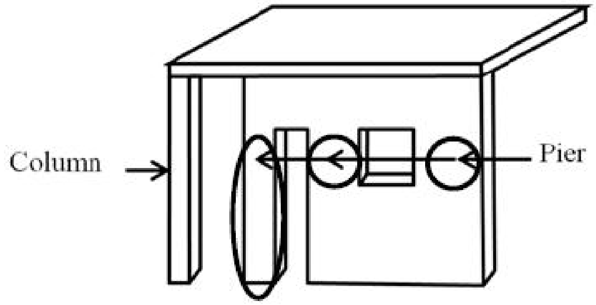
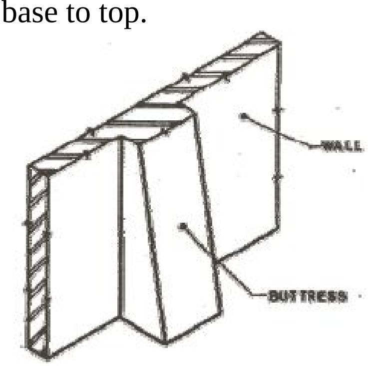
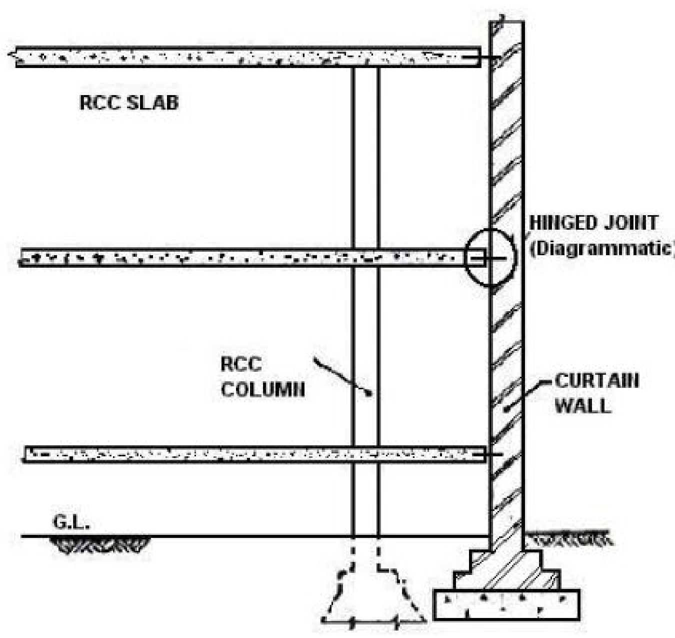
Terminologies in Structural Masonry

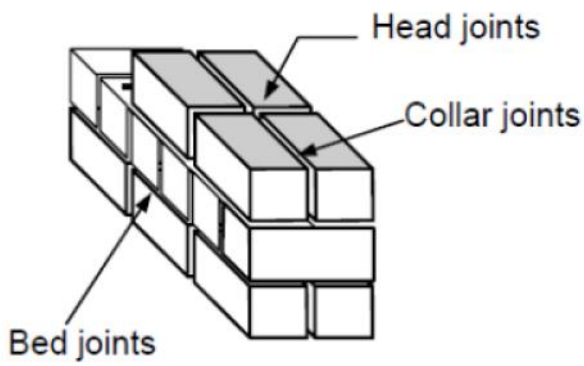
Table 1: Terminologies and abbreviations commonly referred in Structural Masonry

Sl. No.	**Terminology**	**Definition and remarks**
	Bed Block	A block bedded on a wall, column or pier to disperse a concentrated load on a masonry element.
	Cross-Sectional Area of Masonry Unit	Net cross-sectional area of a masonry unit shall be taken as the gross cross-sectional area minus the area of cellular space. Gross cross-sectional area of cored units shall be determined to the outside of the coring but cross-sectional area of grooves shall not be deducted from the gross cross-sectional area to obtain the net cross sectional area <u>Remark:</u> Net section area is difficult to ascertain especially in hollow masonry units. In case of full mortar bedding as shown in Fig 10.1 it is the gross sectional area based on the out-to-out dimension minus hollow spaces. Often alignment of cross webs is not possible while laying hollow units and the load transfer takes place through mortars on the face shells only. In such cases, it is conservative to base net cross-sectional area on the minimum face shell thickness.  Net cross sectional area = shaded area or gross area if the block is more than 75% solid  **Net area = shaded area = full-mortar bedding area** 

		Net area = shaded area if face-shell bedding is adopted (provided alignment of cross webs is ensured)
	Grout	A mixture of cement (or any binding material), sand and water of pourable consistency for filling small voids. Remark: used extensively for filling the surrounding the reinforcement in masonry
	URM	Un-reinforced masonry
	RM	Reinforced masonry
	MI	Masonry In-fill, the masonry wall between the columns and beams of a frame structure
	EMU	Engineered Masonry Unit – engineered for architectural (colour, shape, texture etc), physical (density) and structural requirement (strength, elasticity and durability)
	HCB	Hollow concrete block (A masonry unit of which net cross-sectional area in any plane parallel to the bearing surface is less than 75 percent of its gross cross-sectional area measured in the same plane)
	ECB	Engineered Concrete Block
	SMB	Stabilized Mud block
	SCB	Solid Concrete Block
	TMB	Table Moulded Brick
	WCB	Wire-cut Brick
	Grouted Hollow Masonry Unit	That form of grouted masonry construction in which certain designated cells of hollow units are continuously filled with grout.
	Grouted Multi-Wythe Masonry	That form of grouted masonry construction in which the space between the wythes is solidly or periodically filled with grout.
	Wythe	A continuous vertical tie of masonry one unit in thickness.
	Grouted Multi-Wythe Masonry	That form of grouted masonry construction in which the space between the wythes is solidly or periodically filled with grout.
	Joint Reinforcement	A prefabricated reinforcement in the form of lattice truss which has been hot dip galvanized after fabrication and is to be laid in the mortar bed joint.   **Ladder type reinforcement** **Truss type reinforcment**
	Prism	An assemblage of masonry units bonded by mortar with or without grout used as a test specimen for determining properties of masonry. (preferably with a height/thickness ratio between 2 to 5)
	Grouted Cavity	Two parallel single leaf walls spaced at least 50 mm apart, effectively

	Reinforced Masonry	tied together with wall ties. The intervening cavity contains steel reinforcement and is filled with infill concrete so as to result in common action with masonry under load.
	Pocket type Reinforced Masonry	Masonry reinforced primarily to resist lateral loading where the main reinforcement is concentrated in vertical pockets formed in the tension face of the masonry and is surrounded by in situ concrete.
	Quetta Bond Reinforced Masonry	Masonry at least one and half units thick in which vertical pockets containing reinforcement and mortar or concrete infill occur at intervals along its length.  **Quetta bond**
	Specified Compressive Strength of Masonry	Minimum Compressive strength, expressed as force per unit of net cross- section area, required of the masonry used in construction by the contract document, and upon the project design is based. <u>Remark:</u> Whenever the quantity f_m is under the radical sign, the square root of numerical value only is intended and the result has units of MPa.
	Wall Tie	A metal fastener which connects wythes of masonry to each other or to other materials.
	Bond	Arrangement of masonry units in successive courses to tie the masonry together both longitudinally and transversely; the arrangement is usually worked out to ensure that no vertical joint of one course is exactly over the one in the next course above or below it, and there is maximum possible amount of lap.
	Column	An isolated vertical load bearing member, width of which does not exceed four times the thickness.
	Pier	It is an isolated vertical member whose horizontal dimension measured at right angles to its thickness is not less than 4 times its thickness and whose height is less than 5 times its length.

		 **Column and pier**
	Buttress	A pilaster of masonry built as an integral part of wall and projecting from either or both surfaces, decreasing in cross-sectional area from base to top.  **Buttress**
	Curtain Wall	A non-load bearing wall subject to lateral loads. It may be laterally supported by vertical or horizontal structural members, where necessary  **Curtain wall**
	Effective Height	The height of a wall or column to be considered for calculating slenderness ratio.

<table>
<tr><td></td><td>Effective Length</td><td>The length of a wall to be considered for calculating slenderness ratio.</td></tr>
<tr><td></td><td>Effective Thickness</td><td>The thickness of a wall or column to be considered for calculating slenderness ratio.</td></tr>
<tr><td></td><td>Joint</td><td>A junction of masonry units
Remark:
Horizontal joints are known as bed joints
Vertical joints are known as perpends, and if they are perpendicular to the plane of the wall they are known as cross joint
Vertical joints are known as collar joints if they are parallel to the plane of the wall
Wall joints are the junctions of walls


Joints</td></tr>
<tr><td></td><td>Leaf</td><td>Inner or outer section of a cavity wall.</td></tr>
<tr><td></td><td>Lateral Support</td><td>A support which enables a masonry element to resist lateral load and/or restrains lateral deflection of a masonry element at the point of support.
Remark: Lateral support is a primary requirement in structural design of masonry. A lateral support may be provided along either a horizontal or a vertical line, depending on whether the slenderness ratio is based on a vertical or horizontal dimension. Horizontal or vertical lateral supports should be capable of transmitting design lateral forces to the elements of construction that provide lateral stability to the structure as a whole.</td></tr>
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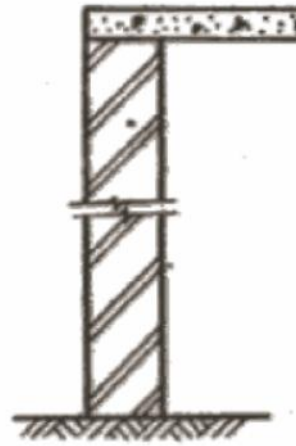
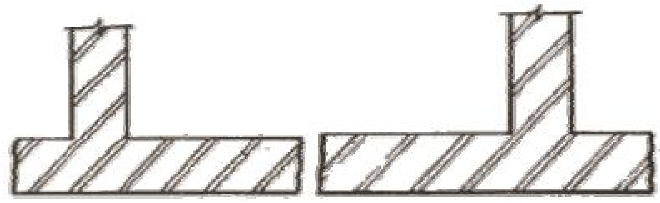
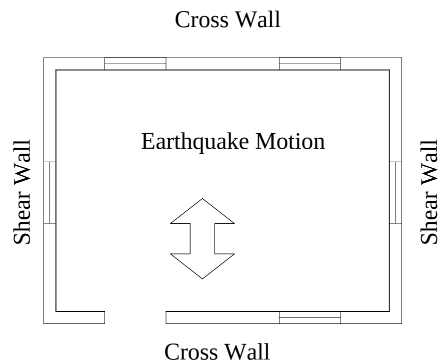
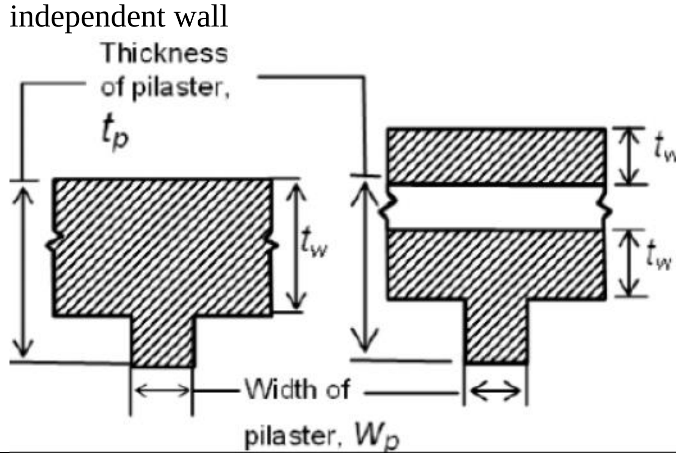
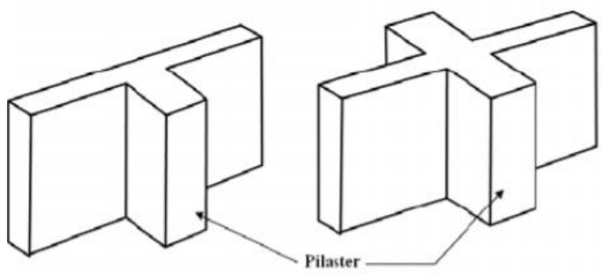
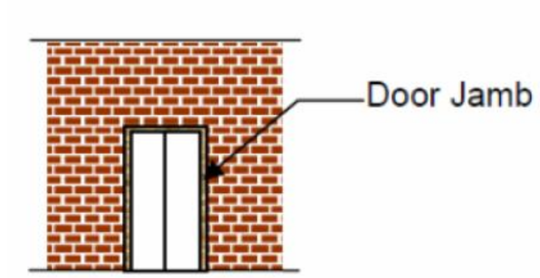
		 **RC slab as a lateral support at the top of wall in the horizontal plane**  **Cross walls as lateral support in the vertical plane**  **Pilasters as lateral supports in the vertical plane**
	Load Bearing Wall	A wall designed to carry an imposed vertical load in addition to its own weight, together with any lateral load.
	Masonry Unit	Individual units which are bonded together with the help of mortar to form a masonry element, such as wall, column, pier and buttress.
	Partition Wall	An interior non-load bearing wall, one storey or part storey in height.
	Panel Wall	An exterior non-load bearing wall in framed construction, wholly supported at each storey but subjected to lateral loads in out-plane direction such as wind loads, earthquake loads etc.
	Shear Wall and Cross wall	A wall designed to carry horizontal forces acting in its plane with or without vertical imposed loads. The walls normal to shear walls are known as cross walls.

		 **Shear walls and cross walls**
	Slenderness Ratio (SR)	Ratio of effective height or effective length to effective thickness of a masonry element.
	Cavity Wall	A wall comprising two leaves, each leaf being built of masonry units and separated by a cavity and tied together with metal ties or bonding units to ensure that the two leaves act as one structural unit, the space between the leaves being either left as continuous cavity or filled with a non-load bearing insulating and waterproofing material.
	Faced Wall	A wall in which facing and backing of two different materials are bonded together to ensure common action under load backing shall be provided by toothing, bonding or other means.
	Veneered Wall	A wall in which the facing is attached to the backing but not so bonded as to result in a common action under load.
	K_s	Stress reduction factor
	K_a	Area reduction factor
	K_p	Shape modification factor
	Pilaster	A thickened section forming integral part of a wall placed at intervals along the wall, to increase the stiffness of the wall or to carry a vertical concentrated load. Thickness of a pilaster is the overall thickness including the thickness of the wall or when bonded into a leaf of a cavity wall, the thickness obtained by treating that leaf as an independent wall 

		 **Pilasters**
	Jamb	Side of an opening in wall.  **Jamb (example: door jamb)**
	Non-Load Bearing Wall	A wall that is not resisting or supporting any loads such that it can be removed with the approval of a structural engineer without jeopardizing integrity of the remaining structure
	Partition Wall	An interior non-load bearing wall, one storey or part storey in height.
	Veneered Wall	A wall in which the facing is attached to the backing but not so bonded as to result in a common action under load.
	Wall Tie	A metal fastener which connects wythes of masonry to each other or to other materials.

Masonry reinforcement

For the purpose of general load bearing construction, Fe 415 grade steel is acceptable, with the generic requirements as given in Table 2. However, for the purpose of earthquake resistant masonry, a variety of reinforcement can be used, typically the ones which impart to the system ductility.

Table 2: Specification for reinforcement in load bearing masonry

Tensile strength	
MS Bars confirming to IS 432 (Part I)	140 MPa for diameter ≤20 mm 130 MPa for diameter >20 mm
HYSD Bars (IS 1786)	230 MPa
Compressive strength	
MS Bars confirming to IS 432 (Part I)	130 MPa
Size and spacing of reinforcement	
The maximum size of reinforcement used in masonry shall be 25 mm diameter bars and minimum size shall not be less than 5 mm.	

The diameter of reinforcement shall not exceed one-half the least clear dimension of the cell, bond beam, or collar joint in which it is placed. Clear distance between parallel bars shall not be less than the diameter of the bars, or less than 25 mm. In columns and pilasters, clear distance between vertical bars shall not be less than 1.5 times the bar diameter, nor less than 35 mm.

Basics of Load Bearing Masonry

It is very important to note that the first step in masonry building design is to ensure a stable configuration. Masonry structures gain stability from the support offered by cross walls, floors, roof and other elements such as piers and buttresses Load bearing walls are structurally more efficient when the load is uniformly distributed and the structure is so planned that eccentricity of loading on the members is as small as possible. Avoidance of eccentric loading by providing adequate bearing of floor/roof on the walls providing adequate stiffness in slabs and avoiding fixity at the supports etc., is especially important in load bearing walls in multistory structures. These matters should receive careful consideration during the planning stage of masonry structures.

In order to ensure uniformity of loading, openings in walls should not be too large. and these should be of 'hole in wall' type as far as possible; Bearings for lintels and bed blocks under beams should be liberal in sizes; heavy concentration of loads should be avoided by judicious planning and sections of load bearing members should be varied where feasible with the loadings so as to obtain more or less uniform stress in adjoining parts of members. One of the commonly occurring causes of cracks in masonry is wide variation in stress in masonry in adjoining parts.

Achieving lateral stability through lateral supports

Lateral support may be in the vertical or horizontal direction, the former consisting of floor/roof bearing on the wall ‘or properly anchored to the same and latter consisting of cross walls, piers or buttresses. These can be achieved by;

a) In case of a wall, where slenderness ratio is based on effective height, any of the following constructions are provided:

(i) RCC floor/roof slab (or beams and slab), irrespective of the direction of span, bears on the supported wall as well as cross walls to the extent of at least 9 cm;

(ii) RCC floor/roof slab not bearing on the supported wall or cross wall is anchored to it with non-corrodible metal ties of 60 cm length and of section not less than 6 x 30 mm, and at intervals not exceeding 2 m as shown in Fig. 1;

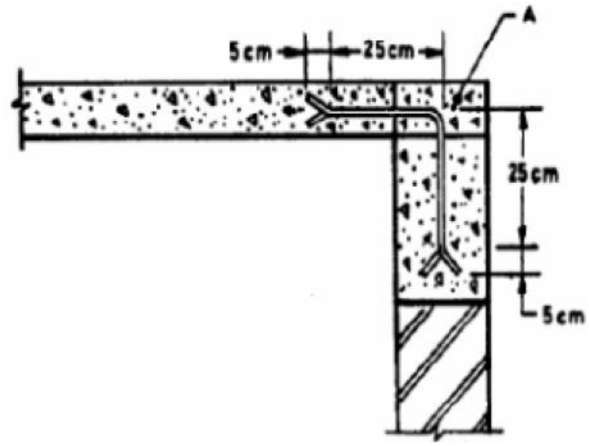


Fig 1: Anchoring a slab when it is not bearing on the wall

(iii) Timber floor/roof and pre-cast floor/roof require special connection details (not covered in this part)

In case of a wall, when slenderness ratio is based on its effective length; a cross wall/pier/buttress of thickness equal to or more than half the thickness of the supported wall or 90 mm, whichever is more, and length equal to or more than one-fifth of the height of wall is built at right angle to the wall (Fig 2) and bonded to it according to provision of 4.2.2.2 (d) of IS 1905 (1987)

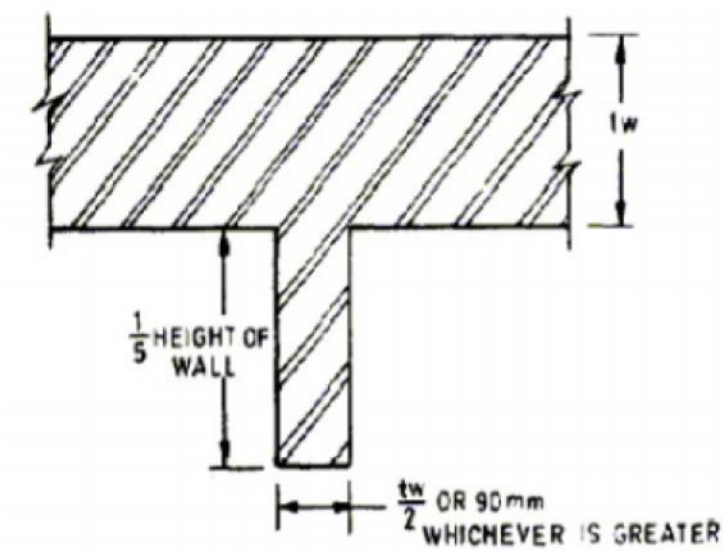


Fig 2: Minimum dimensions for masonry wall/buttress providing effective lateral support

b) In case of a column, an RCC or timber beam/R S joist/roof truss is supported on the column. In this case, the column will not be deemed to be laterally supported in the direction right angle to it; and

c) In case of a column, an RCC beam forming a part of beam and slab construction is supported on the column, and slab adequately bears on stiffening walls. This construction will provide lateral support to the column in the direction of both horizontal axes.

Achieving stability – general

A wall or column subjected to vertical and lateral loads may be considered to be provided with adequate lateral support from consideration of stability, if the construction providing the support is capable of resisting the following forces:

a) Simple static reactions at the point of lateral support to all the lateral loads; plus

b) 2.5 percent of the total vertical load that the wall or column is designed to carry at the point of lateral support.

In case of **load bearing un-reinforced buildings up to four storeys**, stability requirements of may be deemed to have been met with if:

a) Height to width ratio of building does not exceed 2;

b) Cross walls acting as stiffening walls continuous from outer wall to outer wall or outer wall to a load bearing inner wall, and of thickness and spacing as given in Table 10.7 are provided. If stiffening wall or walls that are in a line, are interrupted by openings, length of solid wall or walls in the zone of the wall that is to be stiffened shall be at least one-fifth of height of the opening as shown in Fig 10.8;

c) Floors and roof either bear on cross walls or are anchored to those walls as stated earlier, such that all lateral loads are safely transmitted to those walls and through them to the foundation;

d) And cross walls are built jointly with the bearing walls and are jointly mortared, or the two interconnected by toothing. Alternatively, cross walls may be anchored to walls to be supported by ties of non-corrodible metal of minimum section 6 x 35 mm and length 60 cm with ends bent up at least 5 cm; maximum vertical spacing of ties being 1.2 m).

Table 3: General guidelines for geometry of stiffeners

Thickness (m) of load bearing wall to be stiffened	Height (m) of storey not to exceed	Stiffening wall		
		Thickness (m) not less than		Maximum spacing (m)
		1 to 3 storey	4 storey	
0.1	3.2	0.1	-	4.5
0.2	3.2	0.1	0.2	6.0
0.3	3.4	0.1	0.2	6.0
Above 0.3	5.0	0.1	0.2	8.0

Remark

In case of halls exceeding 8.0 m in length, safety and adequacy of lateral supports shall always be checked by structural analysis.

Trussed roofing may not provide lateral support, unless special measures are adopted to brace and anchor the roofing. However, in case of residential and similar buildings of conventional design with trussed roofing having cross walls, it may be assumed that stability requirements are met with by the cross walls and structural analysis for stability may be dispensed with.

Capacity of a cross wall and shear wall to take horizontal loads and consequent bending moments, increases when parts of bearing walls act as flanges to the cross wall. Maximum overhanging length of bearing wall which could effectively function as a flange should be taken as *12 t* or *H/6*, whichever is less, in case of *T or I* shaped walls and *6 t* or *H/6*, whichever is less, in case of *L or U* shaped walls, where *t* is the thickness of bearing wall and *H* is the total height of wall above the level being considered.

The connection of intersecting walls shall conform to one of the following requirements:

c) Providing proper masonry bonds such that 50% of masonry units at the interface shall interlock.

b) Connector or reinforcement extending in each of the intersecting wall shall have strength equal to that of the bonded wall

c) Requirements of section 8.2.4 of IS: 4326.

Effective overhanging width of flange = 12 *t* or *H*/6 whichever is less, *H* being the total height of wall above the level being considered. Effective overhanging width of flange = 6 *t* or *H*/6 whichever is less, *H* being the total height of wall above the level being considered In case of external walls of basement and plinth stability requirements may be deemed to have been met with if:

a) bricks used in basement and plinth have a minimum crushing strength of 5 MPa and mortar used in masonry is of Grade Ml or better;
b) clear height of ceiling in basement does not exceed 2.6 m;
c) walls are stiffened according to provisions of 4.2.2.1;
d) in the zone of action of soil pressure on basement walls, traffic load excluding any surcharge due to adjoining buildings does not exceed 5 kN/m^2 and terrain does not rise; and
e) Minimum thickness of basement walls is in accordance with Table 4. In case there is surcharge on basement walls from adjoining buildings, thickness of basement walls shall be based on structural analysis.

Table 4: Minimum thickness of basement walls

Height of the ground above basement floor level with wall loading (permanent load)		Minimum thickness (m) of basement walls
More than 50 kN/m	Less than 50 kN/m	
2.75	2.0	0.4
1.75	1.4	0.3

Structural design

The building as a whole shall be analyzed by accepted principles of mechanics to ensure safe and proper functioning in service of its component parts in relation to the whole building. All component parts of the structure shall be capable of sustaining the most adverse combinations of loads, which the building may be reasonably expected to be subjected to during and after construction.

Some general guidance on the design concept of load bearing masonry structures is given in the following paragraphs.

A building is basically subjected to two types of loads, namely:

1. vertical loads on account of dead loads of materials used in construction, plus live loads due to occupancy; and
2. lateral loads due to wind and seismic forces.

While all walls in general can take vertical loads, ability of a wall to take lateral loads depends on its disposition in relation to the direction of lateral load. The lateral loads acting on the face of a building are transmitted through floors (which act as horizontal beams) to cross walls which act as shear walls. From cross walls, loads are transmitted to the foundation. This action is illustrated in Fig. 3. Wind load on the facade wall is transferred via floor slabs to the cross walls and thence to the ground. The strength and stiffness of floors as horizontal girders is vital; hence floors/roofs of lightweight construction should be used with care.

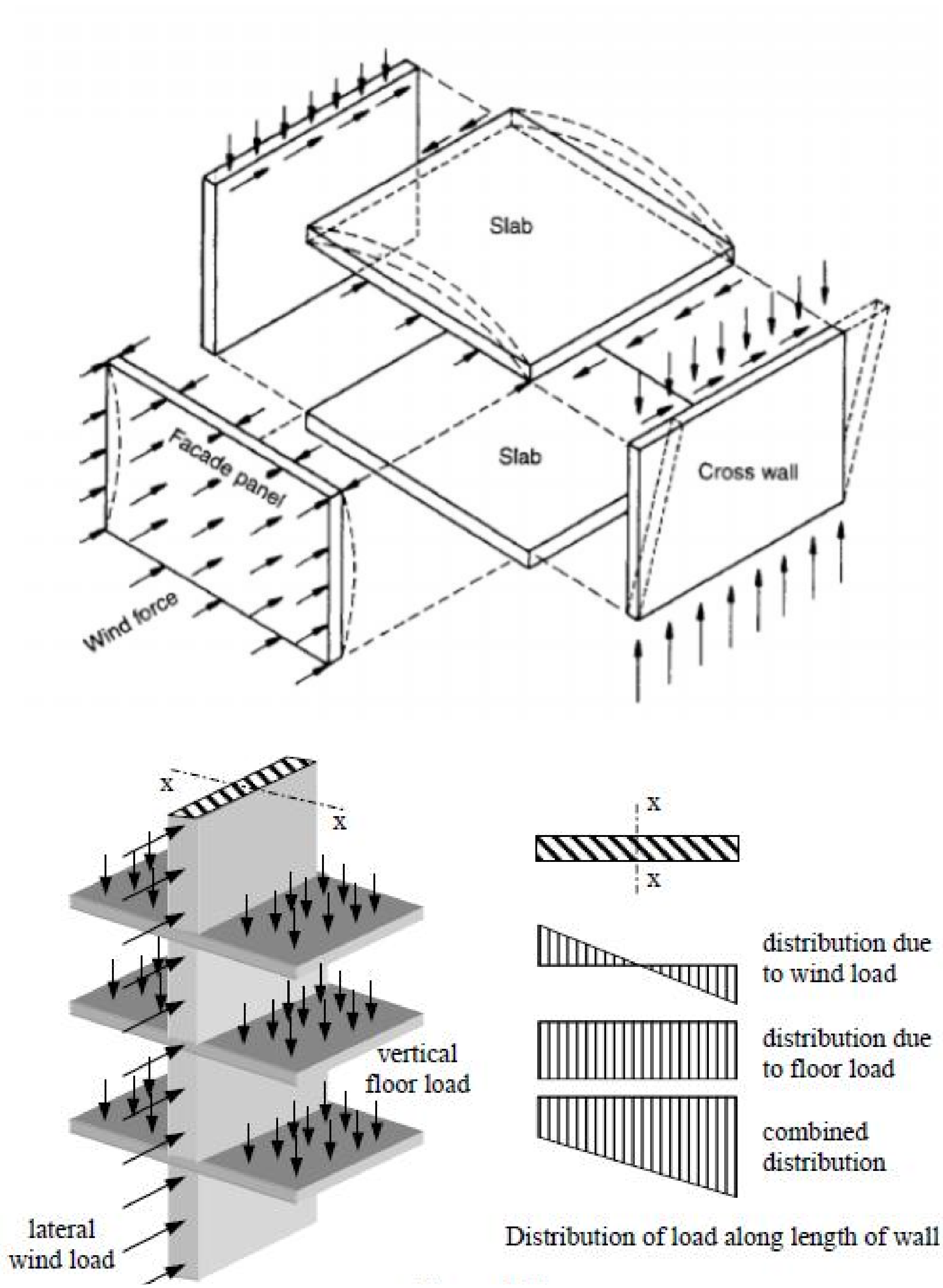


Fig 3: Lateral force (eg. wind force) is resisted by the facade panel owing to bending, and transferred via floor slabs to the cross or shear wall and finally to the ground.

As a result of lateral load, in the cross walls there will be an increase of compressive stress on the leeward side, and decrease of compressive stress on the wind-ward side. These walls should be designed for '**no tension**' and **permissible compressive stress**. It will be of interest to note that a wall which is carrying greater vertical loads will be in a better position to resist lateral loads than the one which is lightly loaded in the vertical direction. This point should be kept in view while planning the structure so as to achieve economy in structural design.

A structure should have adequate stability in the direction of both the principal axes. The so-called 'cross wall' construction may not have much lateral resistance in the longitudinal direction. In multi-storeyed buildings, it is desirable to adopt 'cellular' or 'box type' construction from consideration of stability and economy.

Size, shape and location of openings in the external walls have considerable influence on stability and magnitude of stresses due to lateral loads.

If openings in longitudinal walls are so located that portions of these walls act as flanges to cross walls, the strength of the cross walls get considerably increased and structure becomes much more stable.

Ordinarily a load-bearing masonry structure is designed for permissible compressive and shear stresses (with no tension) as a vertical cantilever by accepted principles of engineering mechanics. No moment transfer is allowed for, at floor to wall connections and lateral forces are assumed to be resisted by diaphragm action of floor/roof slabs, which acting as horizontal beams, transmit lateral forces to cross walls in proportion to their relative (moment of inertia).

Design Loads

Loads to be taken into consideration for designing masonry components of a structure are:

a. dead loads of walls, columns, floors and roofs;
b. live loads of floors and roof;
c. wind loads on walls and sloping roofs and
d. seismic forces.

Note - When a building is subjected to other loads, such as vibration from railways and machinery, these should be taken into consideration according to the best engineering judgment of the designer.

Dead loads

Dead loads shall be calculated on the basis of unit weights taken in accordance with IS:875 – part I (1987).

Live Loads and Wind Loads

Design loads shall be in accordance with the recommendations of IS: 875- (1987) or such other loads and forces as may reasonably be expected to be imposed on the structure either during or after construction.

Note - During construction, suitable measures shall be taken to ensure that masonry is not liable to damage or failure due to action of wind forces, back filling behind walls or temporary construction loads.

Seismic loads

Seismic loads shall be determined in accordance with the IS 1893- Part 1:2002.

Load combinations

In the allowable stress design method followed for the structural design of masonry structures as outlined in this code, adequacy of the structure and member shall be investigated for the following load combinations:

a) DL + IL
b) DL + IL + (WL or EL)
c) DL + WL
d) 0.9 DL +EL

Note: The four load combinations given are consistent with those in other BIS codes. In case of wind and earthquake loads, the reversal of forces needs to be considered. The structure is to be designed for the critical stresses resulting from these load combinations.

Permissible stresses and loads

Permissible stresses and loads may be increased by one-third for load case b, c, & d when wind or earthquake loads are considered along with normal loads.

As an alternative of using an increased permissible stress value when checking safety of structural components, one can use a 25% reduced load for load combinations involving wind or earthquake forces and compare with full permissible stress values. Thus, the modified load combinations b, c and d will be:

a) 0.75 [DL + IL + (WL or EL)]
b) 0.75 [DL + WL]
c) 0.75 [0.9DL +EL]

Vertical load dispersion

Generally, it is accepted, based on experiments, that dispersion of axial loads does not take place at an angle 45° to vertical as assumed in previous codes. An angle of distribution for axial loads not exceeding 30° is more realistic and is recommended by various other masonry codes.

In case of buildings of conventional design with openings of moderate size which are reasonably concentric, some authorities on masonry recommend a simplified approach for design. In simplified approach, stress in masonry at plinth level is assumed to be uniformly distributed in different stretches of masonry, taking loadings in each stretch of masonry walls without making any deduction in weight of masonry for the openings. **It is assumed that the extra stresses obtained in masonry by making no deduction for openings, compensates more or less for concentrations of stresses due to openings**. This approach is of special significance in the design of multi-storeyed load-bearing structure where intervening floor slabs tend to disperse the upper storey loads more or less uniformly on the inter-opening spaces below the slabs and thus at plinth level stress in masonry, as worked out by the above approach is expected to be reasonably accurate.

Lintels

Lintels, that support masonry construction, shall be designed to carry loads for masonry (allowing for arching and dispersion, where applicable) and loads received from any other part of the structure. Length of bearing of lintel at each end shall not be less than 9 cm or one-tenth of the span, whichever is more, and area of the bearing shall be sufficient to ensure that stresses in the masonry (combination of wall stresses, stresses due to arching action and bearing stresses from the lintel) do not exceed the stresses permitted.

When location and size of opening is such that arching action can take place, lintel is designed for the load of masonry included in the equilateral triangle over the lintel. In case floor or roof slab falls within a part of the triangle in question or the triangle is within the influence of a concentrated load or some other opening occurs within a part of the triangle, loading on the lintel will get modified as discussed earlier.

Lateral load distribution

Lateral loads from the wind or earthquakes are generally considered to act in the direction of the principal axes of the building structure. The distribution of lateral loads to various masonry wall elements depends on the rigidities of the horizontal floor or roof diaphragm and of the wall elements. If a diaphragm does not undergo significant in-plane deformation with respect to the supporting walls, it can be considered rigid and lateral loads are distributed in various lateral load resisting wall elements in proportion to their relative stiffness. Horizontal torsion developed due to eccentricity of the applied lateral load with the plan centre of the rigidity can cause forces in the wall parallel and perpendicular to load direction. In-plane rigidities are considered in the analysis, which includes both shearing and flexural deformations. Generally rigidities of transverse walls in direction perpendicular to the direction of lateral force, is usually disregarded. However, stiffening effect of certain portion of such walls as permitted by the code, when the stiffening action is significant, i.e. when the method of connection between the intersecting walls and between walls and diaphragms is adequate for the expected load transfer. On the other hand, flexible diaphragms change shape when subjected to lateral loads and are incapable of transmitting torsional forces. The distribution of lateral loads to vertical wall elements takes place in proportion to the tributary area associated with each wall element for vertical loads distribution.

Basic Compressive Strength of Masonry

The basic compressive strength of masonry f_m shall be determined by the (a) unit strength method or by the (b) prism test method. The unit strength method eliminates the expense of prism tests but is more conservative than the prism test method.

(a) Unit strength method

The basic compressive strength of masonry shall be four times of the basic compressive stress which based on the strength of the units and the type of mortar. Unit strength method is based on the compressive strength of masonry units and mortar type, and is developed by using prism test data.

(b) Prism strength method

Basic compressive strength of masonry shall be determined by prism test on masonry made from masonry units and mortar to be actually used in a particular job. This is a uniform method of testing masonry to determine its compressive strength and is used as an alternative to the unit strength method.

Permissible stresses

Permissible compressive stress in masonry shall be based on the value of basic compressive stress (f_b) which is based on two approaches, (i) when prism is not tested and (ii) when prism is tested.

Prism not tested/Unit Strength Method:

Values of basic compressive stress given in Table 5 which are based on the crushing strength of masonry unit and grades of mortar, and hold good for values of SR not exceeding 6, zero eccentricity and masonry unit having height to width ratio (as laid) equal to 0.75 or less.

Prisms tested:
The basic compressive stress can be obtained by multiplying the specified compressive strength obtained from prism test with a factor of 0.25.

Permissible Compressive Stress

Permissible compressive stress in masonry shall be based on the value of basic compressive stress (f_b) as given in Table 4 and multiplying this value by factor known as stress reduction factor (k_s), Area reduction factor (k_a) and shape modification factor (k_p). Amongst these, the stress reduction factor plays a very important role. It can be explained with the help of fig. 4 and to fig. 5. When the prism (or a short wall) is axially loaded, it can withstand maximum load. As the wall becomes slender, the load carrying capacity reduces and when the loads are eccentric, the load carrying capacity becomes even lesser. Thus the slenderness ratio (SR) and the eccentricity of load (or e/t ratio) plays an important role is the estimation of load capacity of walls. This is presented in Table 6. In the present Indian code, the stress reduction factors are unity for SR=6 and all values of e/t, this is not the case in the other masonry codes. Also the stress reduction factors are to be taken for any type of masonry, but current literature indicates clearly that both, the strength and elasticity of masonry play a role in the reduction factors.

Area reduction factor due to 'small area' of a member is based on the concept that there is statistically greater probability of failure of a small section due to sub-standard units as compared to a large element. However some codes do not include any provision for smallness of area. In view of the fact that strength of masonry units being manufactured at present in our country can appreciably vary, the necessity for this provision is justified in our code. This factor is applicable when sectional area of the element is less than 0.2 m^2. The factor k_a=0.7 + 1.5 A, A being the area of section in m^2.

Shape modification factor is based on the general principle that lesser the number of horizontal joints in masonry, greater its strength or load carrying capacity. This is presented in table 5. Here also there is a need for further studies.

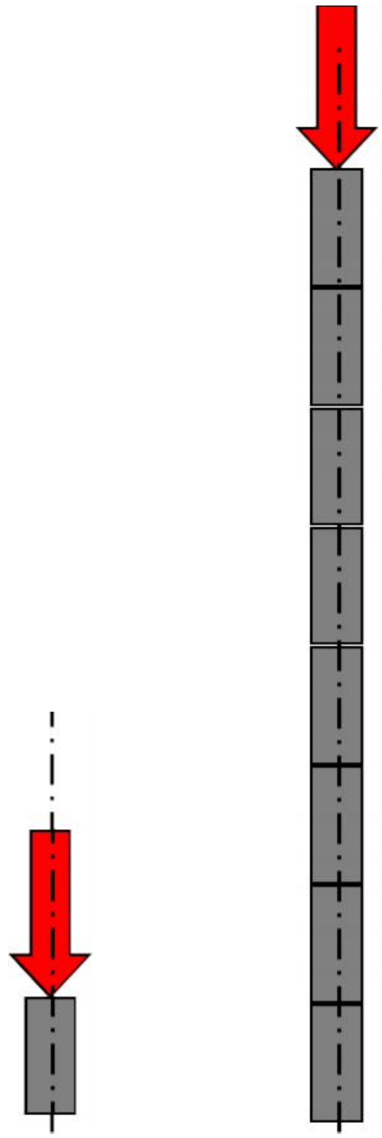


Fig. 4: (a) Short and axially loaded wall (capacity 100%) (b) Slender and axially loaded wall (capacity < 100%)

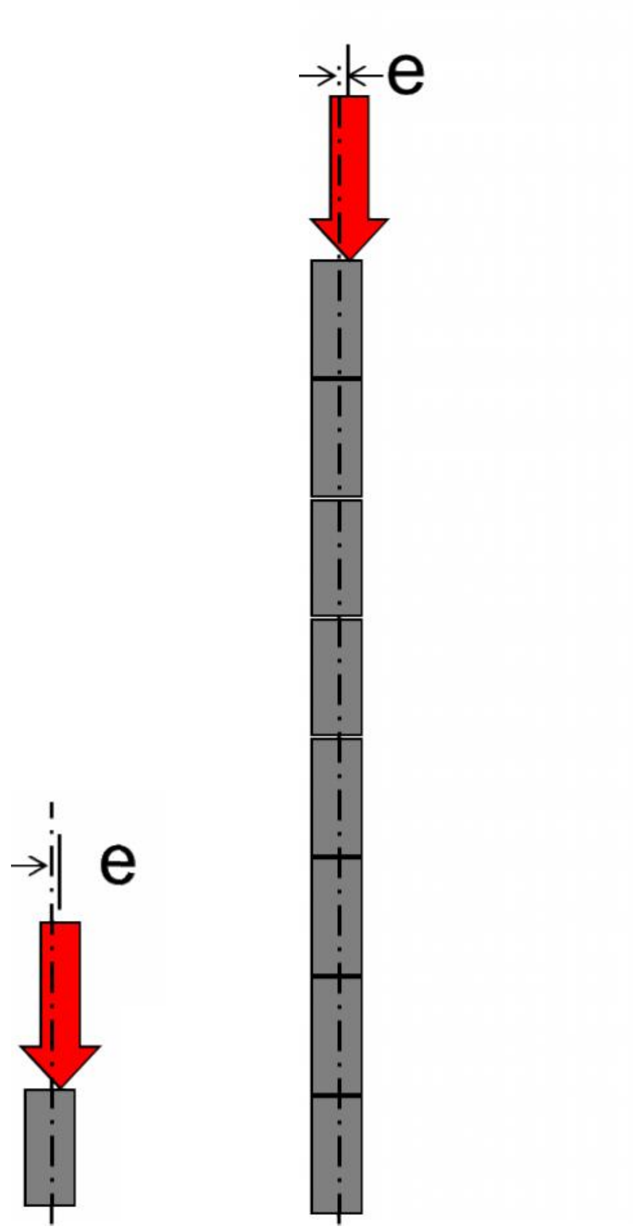


Fig. 5: (a) Short and eccentrically loaded wall (capacity < 100%) (b) Slender and eccentrically loaded wall (capacity << 100%)

Table 5: Basic Compressive strength (in MPa)

Sl. no	Mortar Type	Table 10: Basic compressive strength in MPa corresponding to masonry units of which height to width ratio does not exceed 0.75 and crushing strength in MPa is not less than											
		3.5	**5.0**	**7.5**	**10**	**12.5**	**15**	**17.5**	**20**	**25**	**30**	**35**	**40**
1	**H1**	0.35	0.50	0.75	1.00	1.16	1.31	1.45	1.59	1.91	2.21	2.50	3.05
2	**H2**	0.35	0.50	0.74	0.96	1.09	1.19	1.30	1.41	1.62	1.85	2.10	2.50
3	**M1**	0.35	0.50	0.74	0.96	1.06	1.13	1.20	1.27	1.47	1.69	1.90	2.20
4	**M2**	0.35	0.44	0.59	0.81	0.94	1.03	1.10	1.17	1.34	1.51	1.65	1.90
5	**M3**	0.25	0.41	0.56	0.75	0.87	0.95	1.02	1.10	1.25	1.41	1.55	1.78
6	**L1**	0.25	0.36	0.53	0.67	0.76	0.83	0.90	0.97	1.11	1.26	1.40	1.06
7	**L2**	0.25	0.31	0.42	0.53	0.58	0.61	0.65	0.69	0.73	0.78	0.85	0.95

Table 6: Stress reduction factors (k_s)

Slenderness Ratio	Eccentricity of loading divided by the thickness of the member					
	0	1/24	1/12	1/6	1/4	1/3
(1)	(2)	(3)	(4)	(5)	(6)	(7)
6	1.00	1.00	1.00	1.00	1.00	1.00
8	0.95	0.95	0.94	0.93	0.92	0.91
10	0.89	0.88	0.87	0.85	0.83	0.81
12	0.84	0.83	0.81	0.78	0.75	0.72
14	0.78	0.76	0.74	0.70	0.66	0.66
16	0.73	0.71	0.68	0.63	0.58	0.53
18	0.67	0.64	0.61	0.55	0.49	0.43
20	0.62	0.59	0.55	0.48	0.41	0.34
22	0.56	0.52	0.48	0.40	0.32	0.24
24	0.51	0.47	0.42	0.33	0.24	-
26	0.45	0.40	0.35	0.25	-	-
27	0.43	0.38	0.33	0.22	-	-

Table. 7: Shape modification factor

Height to width ratio of units(as laid)	Shape modification factor (k_p) for units having crushing strength in MPa			
	5.0	7.5	10.0	15.0
(1)	(2)	(3)	(4)	(5)
Up to 0.75	1.0	1.0	1.0	1.0
1.0	1.2	1.1	1.1	1.0
1.5	1.5	1.3	1.2	1.1
2.0 to 4.0	1.8	1.5	1.3	1.2

Combined Permissible Axial and Flexural Compressive Stress

Members subjected to combined axial compression and flexure shall be designed to satisfy the following:

$$\frac{f_A}{F_a} + \frac{f_B}{F_b} \leq 1$$

Where,

f_a= Calculated compressive stresses due to axial load only

f_b= Calculated Compressive stresses due to flexure only

F_a = Allowable axial compressive stress

F_b = Allowable flexural compressive stress = 1.25 F_a

The unity equation assumes a straight line interaction between axial and flexural compressive stresses for unreinforced masonry sections. This is simple portioning of the available allowable stresses between axial and flexure loads, which can be extended for the biaxial bending, by using the bending stress quotients for both axes. In this interaction formula, the secondary effect of moment magnification for flexure term due to axial loads is not included, which is an error on the unsafe side. However, this error for practical size of walls will be relatively small and large overall safety factor of about 4 is adequate to account for this amplification of flexure term. The code allows 25% increase in allowable axial compressive stress, if it is due to flexure. The permissible flexural compressive stress can be expressed as a function of masonry prism strength as follows:

$F_b = 1.25\ F_a = 1.25 \times 0.25\ f_m = 0.31\ f_m$

Permissible Tensile Stress

As a general rule, design of masonry shall be based on the assumption that masonry is not capable of taking any tension. However, in case of lateral loads normal to the plane of the wall, which causes flexural tensile stress, as for example, panel, .curtain partition and freestanding walls, flexural tensile stresses as follows may be permitted in the design for masonry:

Grade M1 or Better mortar

- 0.07 MPa for bending in the vertical direction where tension developed is normal to bed joints.
- 0.14 MPa for bending in the longitudinal direction where tension developed is parallel to bed joints provided crushing strength of masonry units is not less than 10 MPa.

Grade M2 mortar

- 0.05 MPa for bending in the vertical direction where tension developed is normal to bed joints.
- 0.10 MPa for bending in the longitudinal direction where tension developed is parallel to bed joints provided crushing strength of masonry units is not less than 7.5 MPa.

Important note:

No tensile stress is permitted in masonry in case of water-retaining structures in view of water in contact with masonry. Also no tensile stress is permitted in earth-retaining structures in view of the possibility of presence of water at the back of such walls.

Permissible shear stress

In-plane permissible shear stress (Fv)shall not exceed any of :

(a) 0.5 MPa

(b) $0.1 + 0.2f_d$

(c) $0.125\ (f_m)^{1/2}$

Where,

f_d = compressive stress due to dead loads in MPa.

Unreinforced masonry in shear fails in one of the following mode (a) Diagonal tension cracking of masonry generally observed when masonry is weak and mortar is strong, (b) Sliding of masonry units along horizontal bed joint, especially when masonry is lightly loaded in vertical direction and (c) Stepped cracks running through alternate head and bed joints, usually observed in case of strong units and weak mortars. Permissible shear stress for unreinforced masonry is based on experimental research for various failure modes. At low pre-compression (<2 MPa), for sliding type of failure mode, a Mohr-Coulomb type failure theory is more appropriate and shear capacity is increased due to increase in the vertical load. The coefficient of friction of 0.2 has been long used in the masonry codes, however, the recent research indicate that a higher value (about 0.45) is more appropriate. At large pre-compression (> 2 MPa), tensile cracking of masonry is more likely which are expressed in terms of square root of compressive strength of masonry.

Wall Thickness (Cross-Section and Dimensions)

Walls and Columns Subjected to Vertical Loads: Walls and columns bearing vertical loads shall be designed on the basis of permissible compressive stress. Design involves in determining thickness in case of walls and the section in case of columns in relation to strength of masonry units and grade of mortar to be used, taking into consideration various factors such as slenderness ratio, eccentricity, area of section, workmanship, quality of supervision, etc.

Solid Walls

Thickness used for design calculation shall be the actual thickness of masonry computed as the sum of the average dimensions of the masonry units specified in the relevant standard, together with the specified joint thickness. In masonry with raked joints, thickness shall be reduced by the, depth of raking of joints for plastering/pointing. Brick work is generally finished by either pointing or plastering and with that in view, it is necessary to rake the joints while the mortar is green, in case of plaster work raking is intended to provide key for bonding the plaster with the background. Strictly speaking, thickness of masonry for purposes of design in these cases is the actual thickness less depth of raking. However in case of design of masonry based on permissible tensile stress (as for example, design of a free standing wall), if walls are plastered over (plaster of normal thickness i.e. 12 to 15 mm) with mortar of same grade as used in the masonry or M2 grade whichever is stronger or if walls are flush pointed with mortar of M1 grade or stronger, raking thickness can be ignored.

Concepts for earthquake resistant masonry

The basic principles of design and detailing, as outlined in the codes of practice, of earthquakes resistant structures are intentionally simple and generally easy to adopt. Essentially the principles are focused on,

(i) Achieving strength and ductile behaviour
(ii) Maintaining structural integrity

This means that the primary requirement is ‘prevention of catastrophic collapse of buildings or their components’. It is also the intention of the codes of practice to achieve this in relatively simple and cost effective manner.

The level of resistance aimed for in earthquake resistant design is based on the concept of ‘acceptable risk’, with the following objectives;

- To resist minor earthquakes without damage
- To resist moderate earthquakes without significant structural damage, but with some non-structural damage
- To resist major (or severe) earthquake without major failure of the structural framework of the building or its components, to prevent loss of life and to allow safe escape passage for the inmates of the building.

However, certain important critical structures hospitals, power generating units, communication set-ups etc., shall be designed to remain operational during and after an earthquake event.

Un-reinforced masonry buildings are very common in rural and semi-urban area of India. A variety of load bearing masonry units such as adobe, stone, burnt brick, concrete blocks and stabilized mud blocks are commonly used along with a variety of mortars such as mud mortar, cement mortar, lime mortar and composite mortar. Normally these buildings are designed for vertical loads and since masonry has adequate compressive strength, the structure behaves well as long as the loads are vertical.

The behaviour of a masonry building during ground motion can be understood by analysing the nature of stress distribution in the walls of the masonry building. When dominant ground motion is along one axis of the building, the walls parallel to the direction of ground motion are known as ‘shear walls’ and those orthogonal to it are known as ‘cross walls’.

Shear walls are predominantly subjected to in-plane shear stresses and in-plane bending stresses. The in-plane bending stresses in shear walls are normal-to-bed joints. The in-plane shear stresses are responsible for the typical X-type of cracking in the shear walls, while the in-plane bending stresses in the shear walls tend to cause separation of cross walls and shear walls at the junction. Although severe cracking could be caused, the walls may not readily collapse unless a component of ground motion is normal to it. The stress concentration near the openings in shear walls adds to the vulnerability.

The failure pattern of such masonry structures during earthquake can be classified as under (shown in plates 1 to 7);

a) Out-of-plane flexural and/or out-of-plane shear failure

b) In-plane shear and/or in-plane flexure failure

c) Separation of walls at junction

d) Failure of masonry piers between openings

e) Local failures

f) Buckling of wythes

g) Separation of roof from walls

Plate 1: Out-of-plane flexure failure

Plate 10.6: In-plane shear failure

Plate 2: Separation of wall at junctions

Plate 3: Failure of masonry piers between openings

Plate 4: Local failures

Plate 5: Buckling of wythes

Plate 6: Separation of roof from walls

Concept of ‘Containment Reinforcement’

The pattern of failure of masonry buildings during an earthquake makes it clear that the prevention of sudden flexural failure of masonry wall is critical to ensure an earthquake resistant masonry structure. Since flexural tension can occur on both the faces of the wall due to reversal of stresses during an earthquake, there is a need to provide ductile reinforcement on both the faces. This can be accomplished by placing vertical reinforcement either on the surface or close to the surface and surrounding the wall, which is termed as “containment reinforcement”. For the containment reinforcement to be effective, it is essential for it to remain hugged to the wall all times during an earthquake. In order to meet this objective and to prevent buckling of the reinforcement on the compression side of the wall, the vertical reinforcement on either face of the wall to be connected to each other, through horizontal ties/links passing through the bed joint of masonry. Containment reinforcement is intended to permit large ductile deformation and avoid total collapse. In other words, containment reinforcement will act as main energy absorbing element of the wall which otherwise is poor energy absorbing capacity. Fig 6 shows a schematic diagram of containment reinforcement for a typical masonry wall with ties at bed joints. The complete scheme of vertical and horizontal reinforcement is shown in Fig 7.

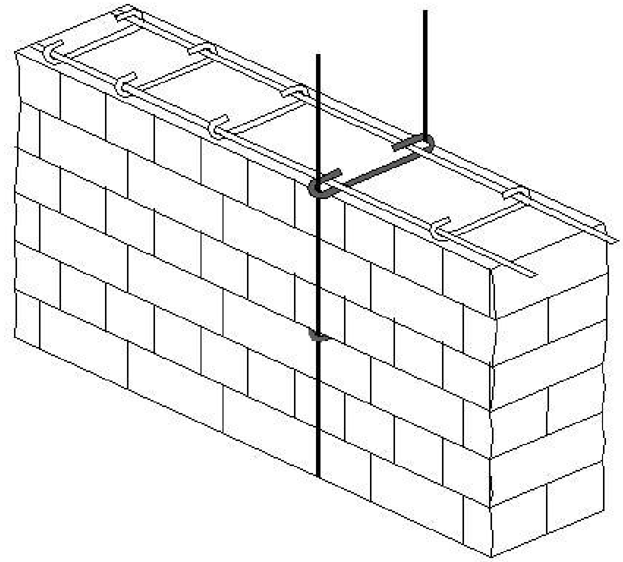


Fig 6: Containment reinforcement scheme integrated with horizontal bed reinforcement

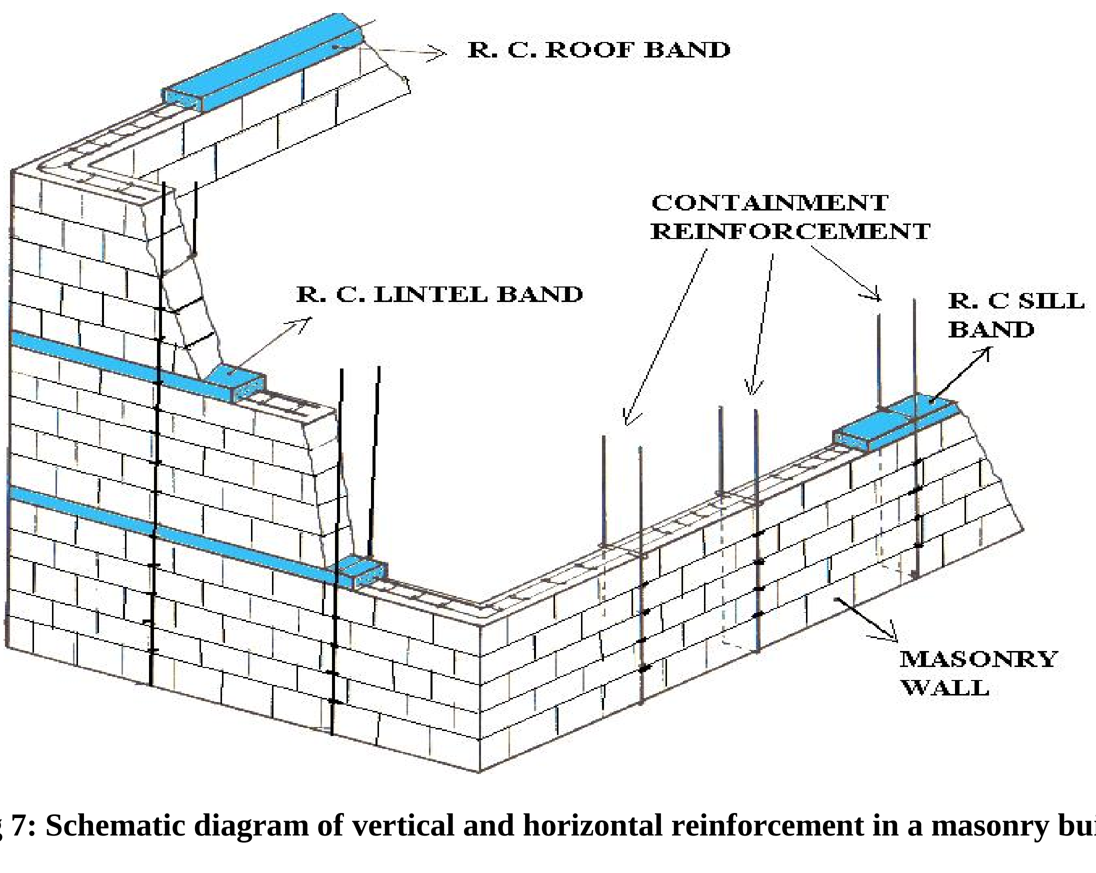


Fig 7: Schematic diagram of vertical and horizontal reinforcement in a masonry building

Specification for vertical 'containment reinforcement'

(i) It is recommended that containment reinforcement may be provided for low-rise (up to 3 storey load bearing) masonry buildings in earthquake zones III, IV, and V. This is in addition to horizontal bands.

(ii) In case of buildings with heavy roofs/floors (mass of the floor more than 200kg/m^2), if height of the wall is 3.0m or less and the length of the wall is less than or equal to 3.0m containment reinforcement need not be provided if there are no openings in the wall.

(iii) Masonry buildings with light roofs (tiled roof, asbestos or zinc sheet roofs) must have containment reinforcement on all walls irrespective of the aspect ratio of the wall.

(iv) Walls with height greater than 3.0m must invariably have containment reinforcement.

(v) All door and window jambs must have containment reinforcement on either sides of the opening at a distance of 150.0mm to 200.0mm from the jamb. Masonry piers between door and window openings or between two window openings should not be less than 0.75m in width. This is a modification of clause 8.3.1 in IS: 4326 (1993). Other provision in this clause may not be changed.

(vi) The wires/rods of containment reinforcement must be tied to the steel in the horizontal band to form a coarse two-dimensional cage holding the masonry in place.

(vii) Normally, the horizontal spacing between two sets of containment reinforcement should be between 0.75m to 1.25m.

(viii) A variety of reinforcing materials can be used as containment reinforcement. The details are presented in Table 8.

Table – 8: Different materials for 'containment reinforcement'

Reinforcing material	Remarks
Mild steel rods/flats	6mm rods available, very ductile, liable to corrosion if exposed and hence has to be either coated with non-corrosive paints or covered with plaster. 20-25mm wide, 3mm thick MS flats could also be used, holes could be made at regular intervals to insert links/bolts to tie the flats provided on both faces of the wall.
Galvanized Iron (GI) wires/flats	Any diameter wire available, easy for handling, good ductility, liable to corrosion and hence has to be protected. 20-25mm wide, 3mm thick GI flats could be used as mentioned above.
Stainless steel	Ideal material for containment reinforcement, 3mm to 4mm wires at 1.0m spacing, no need of coating, plastering etc.
Timber battens	Good quality battens (teak wood, sal wood etc.) of size 50mm x 25mm at 1.0m spacing, the pair of batten on either face of the wall to be tied together at two points at the base and two points at the top by boring a hole and inserting a bolt; needs regular maintenance to prevent rotting; care to be taken to prevent it from catching fire.
Bamboo/split bamboo	Pairs of bamboo or split (half) bamboos at about 1.0m to 1.5m interval; the poles to be tied at two points at the base and two points at top by using GI wires; less life; can catch fire, hence has to be protected
Ferro-cement strips	Thin ferro-cement strips (about 150.0mm wide) with sufficient amount

	of reinforcing material such as chicken mesh, expanded metal, weld mesh etc. at 1.2m spacing; the strips have to be bonded to the masonry wall by using grouted hooks.
Aluminum	Wires, rods and flats readily available, durable and have good resistance to corrosion, strength and modulus is less and hence large quantity is needed.

List of References

1. IS: 1905- 1987, *"Indian Standard Code of Practice for Structural Use of Unreinforced Masonry"*, Bureau of Indian Standards, New Delhi, India, 3rd Edition, 1987.
2. SP 20 (S & T), 1991 "*Hand book on Masonry Design and Construction*" (First revision), , Bureau of Indian Standards, New Delhi 110002
3. IS-4326-1993 *"Indian Standard Earthquake Resistant Design and Construction of Buildings – Code of Practice"*, Bureau of Indian Standards, (Reaffirmed 1998), Edition 3.2 (2002-2004), New Delhi 110002
4. Dayaratnam P, "*Brick and Reinforced Brick Structures*", Oxford IBH Publishing Co. Pvt. Ltd., New Delhi, India, 1987.
5. Venkataramareddy B V, Jagadish K S and Yogananda M R, "*Specification for the use of Stabilized Mud Blocks for building construction (draft code of practice)*", Proceedings of National Seminar on Application of SMB in Housing and Building, Bangalore, Nov.1988, Vol.2, pp 19-22
6. Venkataramareddy B V and Jagadish K S, "*Properties of soil-cement block masonry*", Masonry International, Vol.3, No.2, 1989, pp 80-84.
7. Durgesh C Rai, "*Proposed Draft Provisions and Commentary on Structural Use of Masonry*", Indian Institute of Kanpur, Document No. IITK-GSDMA-EQ12-V-3.0, IITK-GSDMA-EQ19-V1.0, Kanpur.
8. Jagadish K S, Venkataramareddy B V and Nanjunda Rao K S, "*Alternative Building Materials and Technologies*", New Age International (P) Ltd., Publishers, Bangalore, 2007.
9. Hendry A W, "*Structural Masonry*", Macmillan Press, Second Edition, London, 1998.
10. ENV: 1996-1-1-1995, "*Eurocode 6: Design of masonry structures, Part1-1: General rules and rules for buildings – Rules for reinforced and unreinforced masonry*", Published by European Committee for Standardization, BSI 1996.
11. Hendry A W, Sinha B P and Davies S R, (2004), *Design of Masonry Structures*, Third Edition of Load Bearing Brick Work Design, E and FN Spon publishers (an imprint of Chapman & Hall), London