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Research Paper

Preliminary design of mud-wall using cob and plastic frame for low cost housing

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ABSTRACT

This study proposes an innovative wall system that combines cob and rigid plastic (UPVC) frame to develop a sustainable and cost-effective wall for affordable housing. In this system, cob is infilled into the pockets of a UPVC frame, forming a composite structural element. Two wall types are proposed: type A, as an alternative for traditional load-bearing mud (or earth) walls in earthen houses, and type B, as an alternative to brick infill wall in RCC-framed structures. The design approach capitalizes on the tensile strength of UPVC, the compressive and shear strength of both cob and UPVC, and the buckling resistance provided by the cob. The wall is developed as modular units for ease of construction, dismantling and reinstallation. Structural analysis and design were carried out under dead, live, wind, and seismic loads, following relevant Bureau of Indian Standards (BIS) and New Zealand Standard for engineering design of earth buildings. Results indicate that the proposed wall system is structurally stable and safe, with reduced thickness and material consumption compared to conventional mud (or earth) walls. The inclusion of UPVC enhances tensile resistance, addressing the inherent weakness of mud in tensile strength. Moreover, the system is more economical than traditional mud (or earth) wall technologies and significantly less expensive than traditional brick masonry, offering a potential sustainable alternative wall system for low cost housing in rural area.

1 Introduction

Earth houses are among the earliest forms of human shelter, with evidence of such structures dating back nearly 10,000 years across various ancient civilizations in Asia, Europe, Africa and the America [1, 2]. Historically, these dwellings offered as sustainable, locally sourced, environment friendly and cost-effective housing solution. Following first and second World War, resource constraints prompted countries like Germany and France to revisit and develop earth construction technologies. By the late 20th century, nations such as Australia and New Zealand began advancing earth building practices further [3]. More recently, the global focus on climate change mitigation has led to renewed interest in earth houses for their sustainability, low carbon footprint, and energy efficiency.

About one third of the world population live in earthen house [4]. In developing countries, earth houses continue to serve as an affordable housing solution, particularly for low-income populations. In India, as per the 2011 census [5], total 34%

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houses are earthen (katcha) or semi-earthen (semi-katcha) whereas, in rural India, 44.6% houses are earthen (katcha) or semi-earthen (semi-katcha), highlighting the continued reliance on earth houses for their living.

Several techniques including rammed earth, adobe block, pressed block, cob, and 'wattle and daub' methods are used in the construction of earth houses, each with distinct advantages and limitations.

One of the widely used earthen construction technique around the world is Rammed earth wall [6]. It involves compacting a prepared moist soil within formwork to create solid and load bearing walls [7]. When executed correctly, these walls can last over a century with minimal maintenance [8]. However, this method requires skilled labor and carefully prepared soil to avoid cracking and shrinkage. Another very popular earthen wall technique, adobe construction uses hand-pressed earthen blocks moulded and sun-dried before assembly [9]. While this construction is durable and requiring minimal skill, adobe walls are vulnerable to heavy rainfall (over 625mm/year) [8] and typically have a rough surface finish. A modern advancement, Pressed Earth Blocks are created using mechanical presses [10] and often include stabilizers like cement or lime. These blocks offer improved finish and good durability but require more resources including machinery, labour, and technical expertise. Another popular wall construction technique- 'wattle and daub' system is one of the earliest earthen wall technique in the world [11]. In this type of construction, vertical pillars of bamboo, wood or concrete post are fixed on ground, between which bamboo, reeds, branches or other similar items are woven to make a framework. Then mud is applied on both sides of the framework to make a wall. While easy and low-cost, this method suffers from poor durability due to deterioration by pests, termites, water accumulation or rain splashing.

Another economical and widely practiced method is cob construction, in which a stiff mixture of soil, fibre, and water is placed in successive layers to form walls [12]. The mixture is traditionally shaped by hand into lumps or balls and applied directly without the use of formwork. While the technique is simple and requires no equipment, cob walls are susceptible to shrinkage cracking and exhibit limited structural performance [8].

All these methods primarily rely on locally available soil. When the native soil lacks suitable composition, soil components such as sand, clay, and chemical stabilizers like cement, lime, fly ash etc. are used to modify the native soil. However, addition of soil ingredients or stabilizers require proper knowledge for effective use and increase the cost of work.

Traditional earth walls (except 'wattle and daub') generally exhibit good compressive strength and stability when constructed on suitable foundations. Due to their substantial thickness and mass, these walls can resist compressive load effectively. Their mass also provides inherent resistance against wind load, particularly when the wall height is moderate and the foundation is sound. However, a critical vulnerability arises in the roof systems of such structures, as they are often poorly anchored to the wall, making them susceptible to wind induced uplift and lateral displacement failure.

Under seismic loading, earth wall systems are significantly vulnerable. Their heavy mass (except 'wattle and daub'), coupled with low tensile strength, contributes to poor seismic performance. This has been observed in past earthquakes, where earth houses suffered widespread damage and collapse [13]. Rainfall poses another major threat to the durability of earth walls. Heavy splashing and prolonged exposure to water often lead to erosion, weakening and accelerating degradation.

Additionally, constructing traditional earth houses demands high manual labour, which constitutes a major portion of the total cost. The inclusion of stabilizers, machinery or finishing coat further increases expenses.

To overcome these demerits, this study introduces an innovative design for a low-cost mud wall system that integrates cob as an infill material within a plastic (UPVC) frame, forming a composite structural system. In this configuration, the cob infill provides resistance to compressive and shear force, and prevent buckling of the frame. Meanwhile, the plastic frame is designed to carry tension, shear and part of the compression load. This composite behaviour of cob and plastic frame enhances the structural performance of the wall under various loading conditions.

The proposed wall system (as shown in figure 1 for sloped roof structures and figure 2 for reinforced cement concrete buildings) presents a simple, and sustainable solution for low-cost construction. It eliminates the need for formwork, reduces dependency on skilled labour, and simplifies construction technique while improving structural performance. Most importantly, the system enhances resistance to wind and seismic forces and is expected to require minimal maintenance over its service life. Also, the design prevents a common issue of vertical shrinkage cracking in cob walls by localizing and limiting crack length that offer some flexibility in the clay-sand ratio, enabling the effective use of locally available soils. These attributes collectively highlight the adaptability and potential of the proposed wall system for future applications in low-cost housing.

2 Structural Arrangement

The proposed low-cost mud wall is a composite wall system comprising a UPVC (Unplasticized Polyvinyl Chloride) frame and cob infill. The UPVC frame is first assembled on site, and cob is subsequently placed into the frame's pockets. A three-dimensional representation of the structural arrangement is shown in figures 1–5.

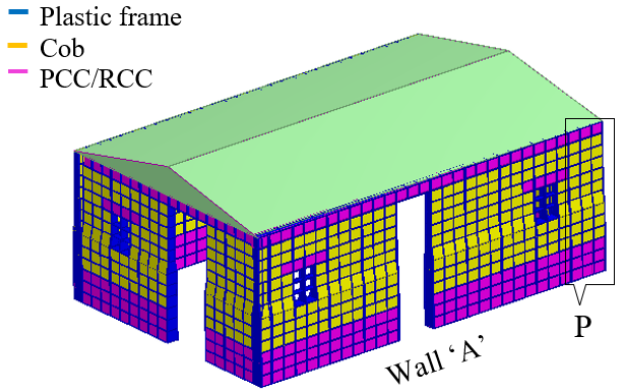


Fig. 1 – Sloped roof house

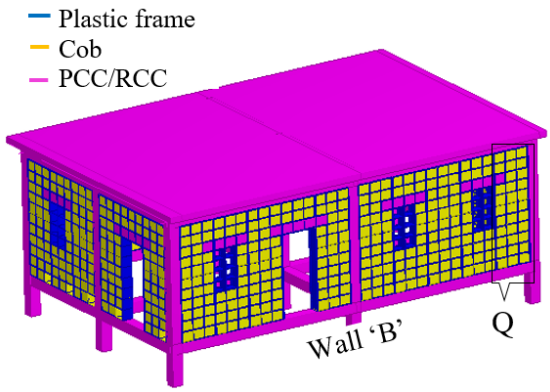


Fig. 2 – RCC house

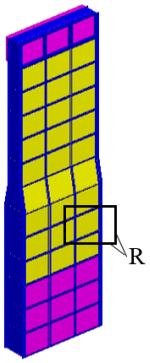


Fig. 3 – 'P' enlarged (Unit module of Wall 'A')

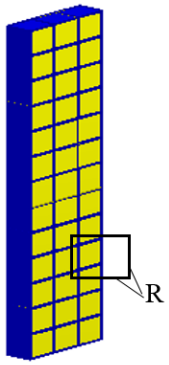


Fig. 4 – 'Q' enlarged (Unit module of Wall 'B')

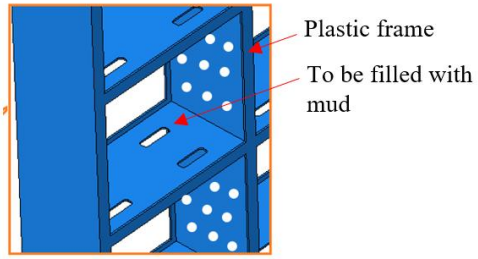


Fig. 5 – Wall portion 'R' without mud

Two wall types are proposed based on the superstructure of a house: 1) Wall Type A for a sloped roof house, functioning as a load-bearing earthen wall and 2) Wall Type B for an RCC-framed house, functioning as an infill or partition wall.

Wall type A serves as a structural load bearing wall intended for traditional earth houses with sloped or lightweight roofs. It provides both vertical and lateral support, ensuring stability for self-weight, imposed loads, and environmental actions such as wind or seismic load. The total height of Wall A is 3.25 meters, including a 0.5 meter below ground level. The subgrade portion is to be constructed using concrete for solid foundation and prevention of moisture ingress. At the top of the wall, a reinforced cement concrete (RCC) bond beam is provided, which contains bottom reinforcement to ensure horizontal continuity and adequate support for the roof. The bond beam also integrate the all wall (in all sides) which help in resisting forces. Dimensional drawings of Wall A are shown in figures 6 and 8.

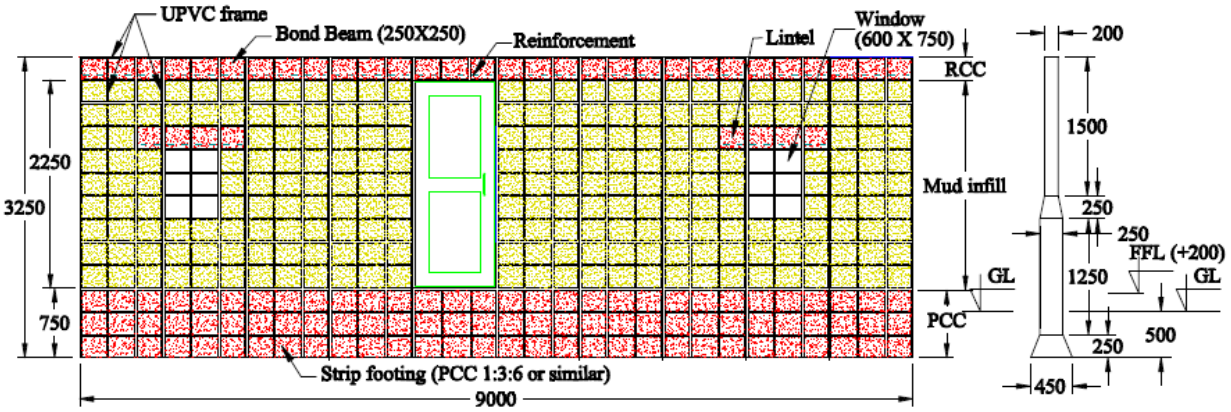


Fig. 6 – Detail of Wall 'A' with side view

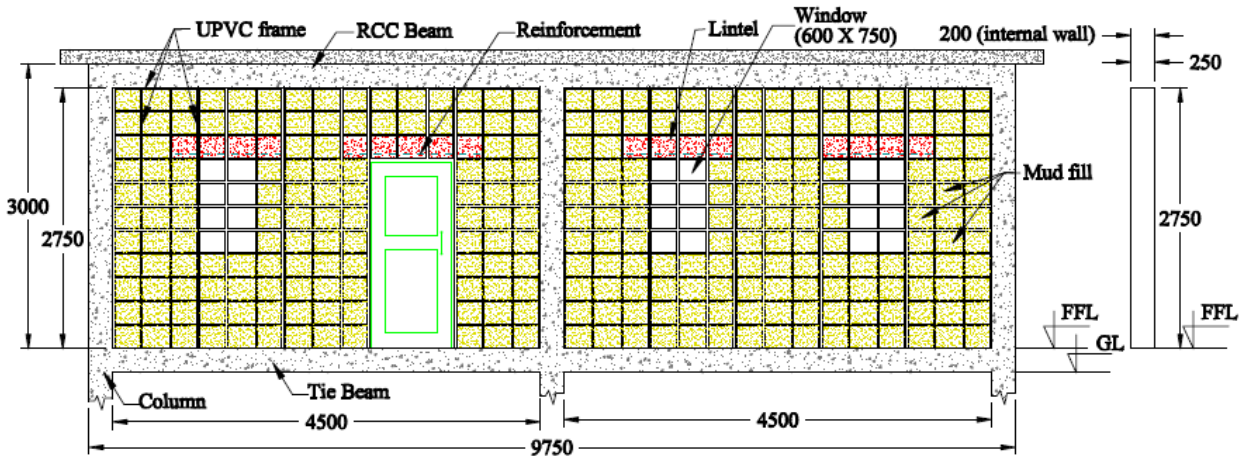


Fig. 7 – Detail of Wall 'B' with side view

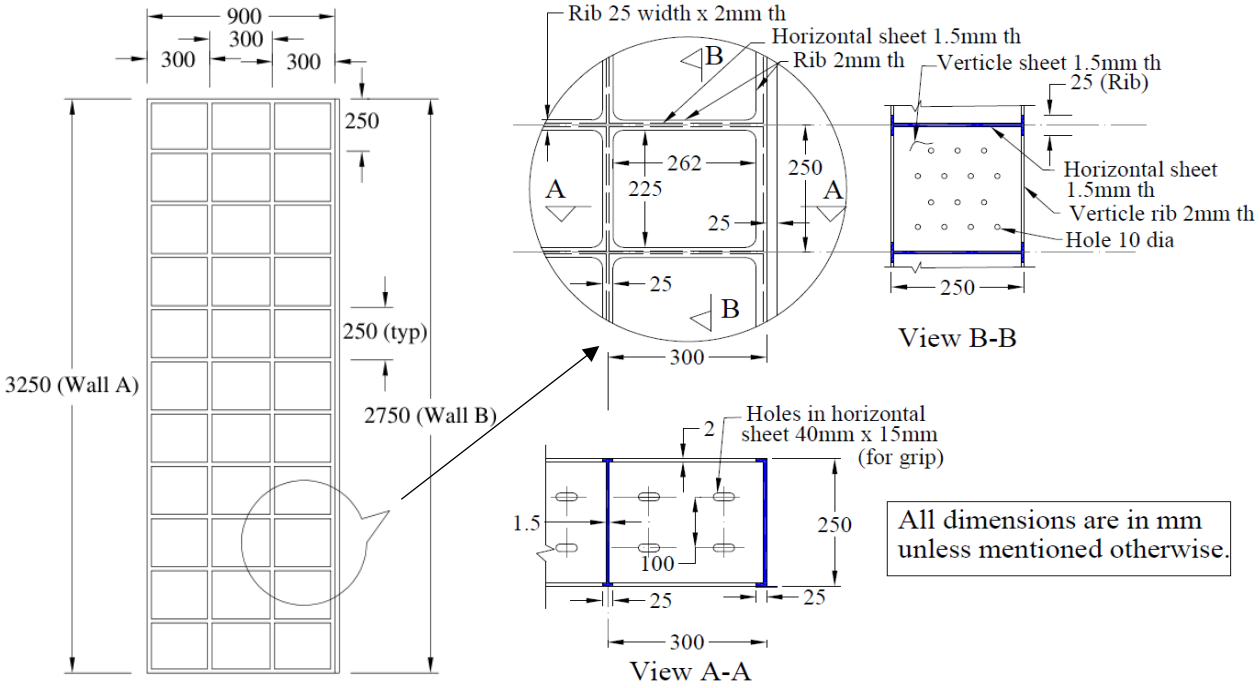


Fig. 8 – Detail of Unit module of UPVC frame

Wall type B is intended as an alternative to conventional brick masonry wall for RCC-framed residential buildings. The proposed wall type B is a non-load-bearing infill wall which will carry its self-weight and transfer lateral loads (e.g., wind, seismic forces etc.) to the adjacent RCC frame. It is to be constructed on a tie beam or on floor slab, and anchored to the RCC beams and columns- either through cement mortar, concrete bedding or mechanical screws. The layout and dimensions of wall type B are shown in figures 7 and 8.

Both wall types, A and B, are composed of modular, repeatable units, each 0.9 meters in width. These modular units are aligned and connected on-site to form a continuous wall system. The structural components common to both wall types include the UPVC frame and the cob infill. A brief description of these components is provided below.

2.1 UPVC Frame

Unplasticized Polyvinyl Chloride (UPVC) is a rigid, durable, and corrosion-resistant polymer widely used in the construction industry for its favourable mechanical and environmental properties. In the proposed design of the low-cost mud wall, UPVC serves as the primary structural framework, providing support to the cob infill in its green state. Its notable properties — including high tensile strength, low weight, ease of assembly, and strong resistance to moisture, termites, and rot — make it highly suitable for structural applications. Additionally, UPVC is recyclable and requires minimal maintenance, aligning well with the objectives of sustainability and cost efficiency.

The proposed wall structure consists of multiple UPVC frame modules. Each modular unit comprises three primary elements: vertical sheets, horizontal sheets, and edge ribs. The geometric configuration and functional roles of these elements are described below.

From a material composition perspective, PVC is a multi-component material in which PVC resin constitutes the primary phase, typically accounting for 70–80% of the formulation and derived from the polymerization of vinyl chloride monomer. To achieve the required processing and performance characteristics, controlled amounts of additives are incorporated, including heat stabilizers (e.g., organotin or mixed-metal stabilizers), lubricants (such as calcium stearate and paraffin wax), and impact modifiers. Fillers, mainly calcium carbonate, are added in small to moderate quantities to enhance stiffness and reduce cost, while pigments such as titanium dioxide provide colour and UV resistance. A typical rigid UPVC formulation, expressed in parts per hundred resin (phr), comprises 100 parts PVC resin with minor additions of stabilizers (~0.3–1 phr), lubricants (~0.5–1.5 phr), fillers (up to ~5 phr or more), and small quantities of modifiers and pigments [14].

2.1.1 Vertical sheet

Each wall module contains four vertical UPVC sheets spaced at 0.3 meter intervals. These sheets provide vertical structural support and define the side boundaries of the cob pockets. The geometry varies by wall type. In Wall A (figure 6), the vertical sheets are 0.45 meters wide at the base, taper to 0.25 meters at a height of 0.25 meters, remain 0.25 meters wide up to 1.5 meters, and then taper again to 0.20 meters at 1.75 meters height before continuing to the top. This variation in width is designed to optimize material usage while enhancing structural stability by increasing base strength, reducing mass toward the top, and minimizing the overturning moment due to self-weight in case of leaning. The geometry of the vertical sheets is illustrated in figures 6-8.

In Wall B, the sheet width is 0.25 meters for external walls and 0.20 meters for internal partitions. The variation in width accounts for greater weathering exposure in external walls and comparatively lower exposure in internal partition walls.

The vertical sheets carry vertical loads, bending moments, and shear forces, while also providing confinement to the cob infill.

2.1.2 Horizontal sheet

Horizontal UPVC sheets connect the vertical sheets at intervals of 0.25 meters along the height. These horizontal elements significantly enhance lateral stability by reducing the effective buckling length of the vertical members. They provide support to the cob mass during the wet and curing stages, and resist horizontal bending moments and shear forces. The geometry of the horizontal sheets is shown in figure 8 (View A–A).

2.1.3 Rib

Ribs are provided at the edges of the vertical and horizontal sheets to enhance structural performance. These ribs reduce the buckling length of both vertical and horizontal sheets and increase the section modulus and radius of gyration of the sheets. As a result, the load-bearing capacity is significantly improved.

Functionally, the ribs also aid the construction process by helping to retain the cob infill within the frame during placement and compaction. Under loading conditions, the ribs provide partial confinement to the cob, which enhances its compressive load bearing strength. Thus, after the cob is cured and dried, the composite frame-consisting of UPVC vertical and horizontal sheets, edge ribs, and the cob infill-forms a rigid structural unit capable of resisting loads acting on the wall.

2.1.4 Cob

Cob is a natural building material composed of a mixture of soil, fibre and water. To prepare cob, the topsoil (typically rich in organic matter) is first removed. The subsoil is then excavated, transported to the site, and processed for cob making. Locally available soil is preferred to minimize the cost associated with transportation.

The soil is prepared by breaking up any lumps and removing foreign objects and residual organic material. It is then thoroughly mixed with water, and fibres are added to produce a stiff, dough like mass. In traditional cob construction, this mix is applied manually in layers to form freestanding walls without the use of formwork. However, in the proposed construction method, the cob is filled into the pockets of UPVC frame. The mix is then hand-compacted and finished using a hand trowel.

Suitable soil types for cob include clayey sand, clayey silt, clayey gravel and clay-sand-gravel mixtures [4]. Soils with a high proportion of silts and sands- such as silty gravels, silty sands and sand-silt-gravel mixtures can also be used if blended with clay or stabilizer (such as cement, lime, or fly ash) [4] properly. An optimal cob mixture typically contains 15–25% clay and 75–85% sand, gravel, and silt, with gravel particles no larger than 6.35 mm [4].

The recommended water to dry-soil ratio is in between 20 to 30% [4]. Lower water content reduces workability, while excess water can lead to shrinkage cracks upon drying.

The fibre improves cob's mechanical and durability properties. Common fibres include straw (most commonly used), coconut coir, wood chips, hemp shives, sheep wool, reed etc. These fibres enhance workability, cohesion, and resistance to cracking. It also improve tensile, shear, flexural strength and overall weather durability. The recommended fibre length is 20 mm to 100 mm, with an optimal content of 1 to 1.5% by weight [15]. Insufficient fibre reduces mechanical performance, while excessive fibre can compromise the compressive strength of the material.

3 Construction Procedure

The construction procedure of the proposed low-cost earth wall utilizing cob and plastic frame is very simple. The following steps outline the construction procedure:

3.1 Site Preparation and Layout

Construction begins with the selection of a suitable site- preferably elevated, well-drained, and free from water stagnation. The building layout is marked at the desired location.

3.2 Foundation Construction

A shallow foundation trench, typically 300–400 mm deep, is excavated along the marked layout. Soil is rammed at the base of the trench for making firm base. If required PCC (1:3:6) of 75-100 mm thick is to be laid for level and firm base.

3.3 Erection of Plastic Frame

Modular UPVC wall frames are placed on the foundation. Door and window position are set at this stage. After placing two walls on opposite sides, roof is constructed and connected to the walls. The plastic frames serve as the structural skeleton. The modular nature of plastic frames facilitates quick installation and alignment.

3.4 Cob Mix Preparation

Topsoil is first removed to expose the underlying subsoil intended for cob preparation. The selected subsoil is then excavated from the borrow area, transported to the construction site. Foreign materials such as stones, roots, and residual organic matter are thoroughly removed and lumps in the soil is broken down. Proper screening and cleaning at this stage are essential to achieve consistency in the final mix. After cleaning, the soil is gradually mixed with an appropriate quantity of water to achieve the desired moisture content. Natural fibres, such as straw or similar reinforcing materials, are then added into the wet soil to enhance tensile strength, reduce shrinkage, and improve crack resistance. The entire mixture is kneaded

and turned repeatedly to evenly distribute all components. This process continues until a cohesive, stiff, dough-like mass with uniform plastic consistency is obtained. After thorough blending, the cob mix is left to rest for a short duration. This resting period allows for better moisture absorption and enhanced internal cohesion. Once the cob achieves a uniform texture and desired consistency, it becomes suitable for use. The prepared mix is then placed and compacted into the pockets of the UPVC frame.

3.5 Wall Construction

After placing cob into UPVC framework, the cob is manually pressed and compacted for uniform filling. Once a layer is compacted, the inner surface is finished flush with the plane of the interior ribs, while the exterior face is finished approximately 10 mm beyond the plane of the outer ribs to enhance water runoff and surface durability. Typically, three to four layers of cob can be applied at a time, followed by a period of partial drying. This staged construction allows each segment to gain sufficient strength before subsequent layers are added, thereby maintaining structural stability during the entire wall construction.

3.6 Finishing

A thorough inspection is performed once all major construction activities are completed. This includes checking for surface imperfections, shrinkage cracks, gaps, or any inconsistencies in alignment or finish. All cracks or voids are repaired using the same cob mixture to ensure material continuity. Uneven surfaces are smoothed out to achieve a uniform appearance. These finishing processes not only enhance the visual appearance but also contribute to the structural and environmental performance of the wall.

4 Preliminary Structural Design

The structural design of the proposed mud-wall system was carried out with the objective of ensuring stability and safety under anticipated loading conditions. The design process included three main components: (i) load calculation, (ii) structural analysis, and (iii) stress check (against allowable limits) and determination of the factor of safety.

4.1 Load Calculation

The loads considered for the structural design included dead load, live load, wind load (IS 875, Part I–III) [16–18], and seismic load (IS 1893:2002) [19]. Dead load accounted for the self-weight of the cob, the plastic frame and the roof structure. Live load was considered as roof live load due to maintenance activities. Wind load was calculated based on a basic wind speed of 47 m/s (169.2 km/h), applicable to many parts of India (including Delhi). Seismic load was considered for moderate seismic intensity (Zone III) in accordance with IS 1893 (2002) [19]. Based on these codes, the applicable loads on wall types A and B are summarized in table 1.

4.2 Structural Analysis

Structural analysis was performed to determine the axial forces, bending moments, and shear forces in the proposed wall types (A and B) under various loading conditions. Table 2 presents the diagrams for axial forces and bending moments, along with maximum values of the induced forces.

In the analysis, wall type A was modelled as fixed at the base (foundation level) and laterally hinge-supported at the top, representing the connection to a roof diaphragm laterally supported by gable walls. Wall type B was considered simply supported (hinged) at both the top and bottom, representing its position between RCC beams. For simplification and conservative design, both wall types were assumed to be supported only along their top and bottom ends, without support along the two vertical edges.

A linear elastic behaviour was assumed for the preliminary analysis. The wall system was analysed for DL, LL, WL and EL. For out-of-plane WL and EL, internal forces were computed based on the aforementioned support conditions. Under in-plane loading, the induced bending moments and shear forces are dependent on the wall length and generally not critical for practical wall dimensions. In the case of in-plane seismic loading, stress concentrations may develop at the corners of wall openings (doors and windows), that may initiate cracks. This aspect, however, is beyond the scope of the present study.

Table 1 - Loads on wall type A and B

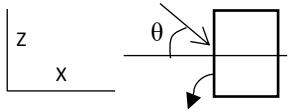
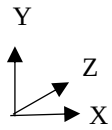
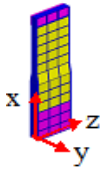
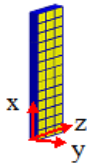
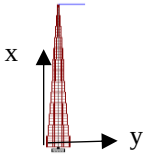
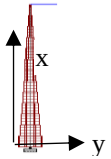
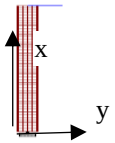
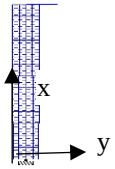
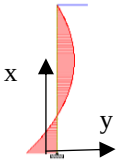
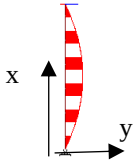
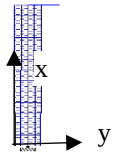
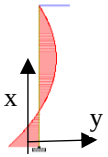
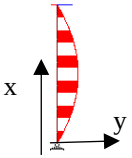
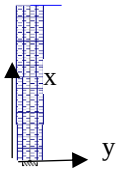
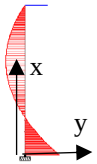
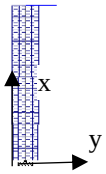
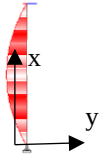
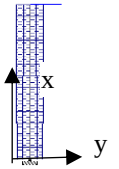
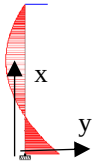
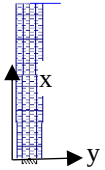
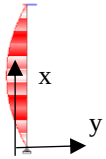
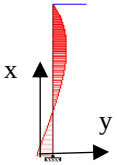
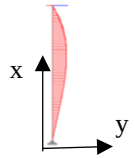
Load Case No.	Load type	Description	Load on wall type A	Load on wall type B	Reference
1	Dead Load (DL)	Self-Weight	5.4 KN/m (Up to 0.75 m ht.)	4.05KN/m (all ht.)	Unit weight of PCC – 24KN/m^3
			4.05 KN/m (From 0.75 m to 1.75 m ht.)		Unit weight of Cob – 18KN/m^3
			3.24 KN/m (From 1.75 m to 3.25 m ht.)		Unit weight of Cob – 18KN/m^3
2	Live Load (LL)	Roof live load (non-accessible roof)	0.75 KN/m^2	NIL (LL will be carried out by RCC frame)	Table 2, IS 875 (part II)
3	Wind Load (WL)	Designed Wind Pressure, $P_z = 0.6V_z^2$ $=0.6*(V_b*K_1*K_2*K_3)^2$ $= 0.6*(47*0.9*0.91*1.0)^2$ KN/m^2 $= 0.89$ KN/m^2	 Global Axis	Wall side A θ = Wind direction	Clause 5.3 and 5.4, IS 875 (part III)
3.1	WL Case I (θ=0º, C_{Pi}= +0.2)	$C_{pe,A}$= +0.7	+0.45 KN/m^2	+0.45 KN/m^2	Table 4, IS 875 (part III)
		$C_{pe,Roof}$= -0.9	-0.98 KN/m^2	-	Table 15, IS 875 (part III)
3.2	WL Case II (θ=0º, C_{Pi}= -0.2)	$C_{pe,A}$= +0.7	+0.80 KN/m^2	+0.80 KN/m^2	Table 4, IS 875 (part III)
		$C_{pe,Roof}$= -0.9	-0.62 KN/m^2	-	Table 15, IS 875 (part III)
3.3	WL Case III (θ=90º, C_{Pi}= +0.2)	$C_{pe,A}$= -0.5	-0.62 KN/m^2	-0.62 KN/m^2	Table 4, IS 875 (part III)
		$C_{pe,Roof}$= -0.9	-0.98 KN/m^2	-	Table 15, IS 875 (part III)
3.4	WL Case IV (θ=90º, C_{Pi}= -0.2)	$C_{pe,A}$= -0.5	-0.27 KN/m^2	-0.27 KN/m^2	Table 4, IS 875 (part III)
		$C_{pe,Roof}$= -0.9	-0.62 KN/m^2	-	Table 15, IS 875 (part III)
4.1	Earthquake Load (EL) +X	EL+X	Force in +X direction due to dead weight of structure.	Force in +X direction due to self-dead weight.	IS 1893, 2002
4.2	Earthquake Load (EL) +Z	EL+Z	Force in +Z direction due to dead weight of structure.	Force in +Z direction due to self-dead weight.	IS 1893, 2002

Table 2 - Structural analysis of wall type A (3.25m height x 0.9m width) and wall type B (3.0m height x 0.9m width)

Sl. No	Load Case	Axial Force Diagram	Bending Moment Diagram	Maximum Force	Axial Force Diagram	Bending Moment Diagram	Maximum Force
		Wall type A (3.25m height x 0.9m width)			**Wall type B (3m height x 0.9m width)**		
							
		Fig. 9 – Global Axis	***Fig. 10 – Wall module A with local axis system***		***Fig. 11 – Wall module B with local axis system***		
1.	Dead Load (DL)	 ***Fig. 12 – Axial Force Diagram* (AFD)**	No Significant Bending Moment (BM) induced in the wall.	At +0.00m level: Axial Force, F_x= 16.7 KN, Compression (C) At +1.75m level: F_x= 6.7 KN (C)	 ***Fig. 13 – AFD***	No Significant Bending Moment (BM) induced in the wall.	*At +0.00m level:* F_x= 12.2 KN (C) *At +1.5m level:* F_x= 6.1 KN (C)
2.	Live Load (LL)	 ***Fig. 14 – AFD***	No Significant Bending Moment induced in the wall.	F_x = 1.9 KN (C)	No Significant Axial Force induced in the wall.	No Significant Bending Moment induced in the wall.	-
3.	WL Case I* (Wind direction +y, C_{pe}= +0.7, C_{pi}= +0.2)	 ***Fig. 15 – AFD***	 ***Fig. 16 – BMD***	*At +0.00m level:* F_x= 2.7 KN (T) M_z= 0.54 KN-m F_y= 0.82 KN *At +1.75m level:* F_x= 2.7 KN (T) M_z= 0.30 KN-m F_y= 0.1 KN	No Significant Axial Force induced in the wall.	 ***Fig. 17 – BMD***	At +0.00m level: F_y= 0.60 KN At +1.5m level: M_z= 0.46 KN-m

Sl. No	Load Case	Axial Force Diagram	Bending Moment Diagram	Maximum Force	Axial Force Diagram	Bending Moment Diagram	Maximum Force
		Wall type A (3.25m height x 0.9m width)			**Wall type B (3m height x 0.9m width)**		
4.	WL Case II (Wind direction +y, C_{pe}= +0.7, C_{pi}= -0.2)	 ***Fig. 18 – AFD***	 ***Fig. 19 – BMD***	At +0.00m level: F_x= 1.7 KN (T) M_z= 0.96 KN-m F_y= 1.5 KN At +1.75m level: F_x= 1.7 KN (T) M_z= 0.56 KN-m F_y= 0.2 KN	No Significant Axial Force induced in the wall.	 ***Fig. 20 – BMD***	At +0.00m level: F_y= 1.1 KN At +1.5m level: M_z= 0.82 KN-m
5.	WL Case III (Wind direction +z, C_{pe}= +0.7, C_{pi}= +0.2)	 ***Fig. 21 – AFD***	 ***Fig. 22 – BMD***	At +0.00m level: F_x= 2.7 KN (T) M_z= 0.8 KN-m F_y= 1.2 KN At +1.75m level: F_x= 2.7 KN (T) M_z= 0.67 KN-m F_y= 0.2 KN	 ***Fig. 23 – AFD***	 ***Fig. 24 – BMD***	At +0.00m level: F_y= 0.88 KN At +1.5m level: M_z= 0.68 KN-m
6.	WL Case IV (Wind direction +z, C_{pe}= +0.7, C_{pi}= -0.2)	 ***Fig. 25 – AFD***	 ***Fig. 26 – BMD***	At +0.00m level: F_x= 1.7 KN (T) M_z= 0.67 KN-m F_y= 0.7 KN At +1.75m level: F_x= 1.7 KN (T) M_z= 0.28 KN-m F_y= 0.2 KN	 ***Fig. 27 – AFD***	 ***Fig. 28 – BMD***	At +0.00m level: F_y= 0.50 KN At +1.5m level: M_z= 0.40 KN-m
7.	EL Case I* (+y direction)	No Significant Axial Force induced in the wall.	 ***Fig. 29 – BMD***	At +0.00m level: M_z= 0.19 KN-m F_y= 0.18 KN At +1.75m level: M_z= 0.12 KN-m	No Significant Axial Force induced in the wall.	 ***Fig. 30 – BMD***	At +0.00m level: F_y= 0.21 KN At +1.75m level: M_z= 0.30 KN-m

* The portal (or moment) frame behavior of the structure was not considered here. In the global structural analysis, appropriate joint stiffness should be accounted to accurately determine the induced forces on the wall. For the EL +z load case, the full wall length with openings should be considered to determine the forces and corner stress at openings.

4.3 Stress check and factor of safety

Induced stresses at critical sections in walls type A and B were determined from the factored loads and critical load combinations based on table 4 of IS 800 (2007) [20]. The induced stresses were then checked against the corresponding material strength properties. Design checks were performed to ensure that stresses remained within permissible limits under critical load combinations. Factors of safety was determined from the ratio of material strength to the maximum induced stress. The critical load combinations, maximum induced forces, induced stresses, and factors of safety are summarized in tables 3 and 4.

The induced internal stresses were determined, considering the wall as a composite section, assuming linear elastic behavior in accordance with Hooke's law, and the theory of plane stress and strain. The resulting stress distribution under combined bending moment and axial load is shown in figure. 31. The cob primarily carries compressive stresses, while the UPVC frame resists tensile stresses and a portion of the compressive load.

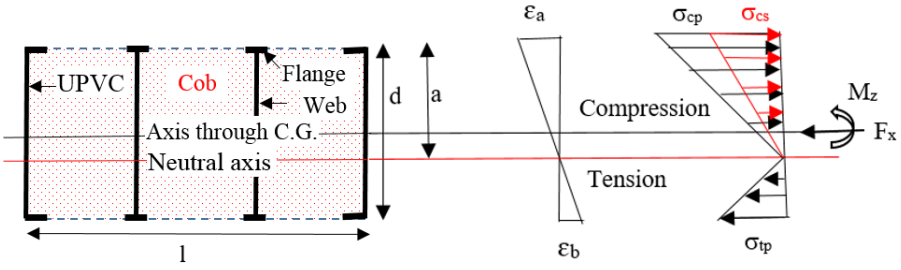


Fig. 31 – Stress diagram in wall cross section

From the stress distribution shown in figure. 31, the following equations are drawn based on force equilibrium and strain compatibility conditions.

When Neutral axis lies inside the section:

From, ∑Fx = 0,

$$A_{f1}\sigma_{cp} + 0.5A_{w1}\sigma_{cp} - 0.5A_{w2}\sigma_{tp} - A_{f2}\sigma_{tp} + 0.5A_s\sigma_{cs} - Fx = 0 \quad (1)$$

From, ∑Mz = 0,

$$A_{f1}\sigma_{cp}\times\frac{t_f}{2} + 0.5A_{w1}s_{cp}\times\frac{a}{3} - 0.5A_{w2}\sigma_{tp}\times\frac{(2d+a)}{3} - A_{f2}\sigma_{tp}\times\left(d-\frac{t_f}{2}\right) + 0.5A_s\sigma_{cs}\times\frac{a}{3} - F_x\times\frac{d}{2} + M_z = 0 \quad (2)$$

From the strain compatibility, $$\sigma_{cp} - \sigma_{cs}\times\frac{E_p}{E_s} = 0 \quad (3)$$

From strain diagram, $$\sigma_{cp}\times(d-a) - \sigma_{tp}\times a = 0 \quad (4)$$

Similarly, when Neutral axis lies outside the section:

$$A_{f1}\sigma_{cp1} + A_w\frac{(\sigma_{cp1}+\sigma_{cp2})}{2} + A_{f2}\sigma_{cp2} + A_s\frac{(\sigma_{cs1}+\sigma_{cs2})}{2} - F_x = 0 \quad (5)$$

$$A_{f1}\sigma_{cp1}\times\frac{t_f}{2} + A_w\sigma_{cp2}\times\frac{d}{2} + A_w\frac{(\sigma_{cp1}-\sigma_{cp2})}{2}\times\frac{d}{3} + A_{f2}\sigma_{cp2}\times\left(d-\frac{t_f}{2}\right) + A_s\sigma_{cs2}\times\frac{d}{2} + A_s\frac{(\sigma_{cs1}-\sigma_{cs2})}{2}\times\frac{d}{3} - F_x\times\frac{d}{2} + M_z = 0 \quad (6)$$

$$\sigma_{cp1} - \sigma_{cs1}\times\frac{E_p}{E_s} = 0 \quad (7)$$

and, $$\sigma_{cp2} - \sigma_{cs2} \times \frac{E_p}{E_s} = 0 \quad (8)$$

and, $$\sigma_{cp1} \times (a - d) - \sigma_{cp2} \times a = 0 \quad (9)$$

Where, A_f = Flange area of UPVC section

A_w = Web area of UPVC section
A_s = Cob (Soil) area
σ_{cp} = Compressive stress on UPVC
σ_{tp} = Tensile stress on UPVC
σ_{cs} = Compressive stress on cob (soil)
t_f = Thickness of flange (UPVC section)
E_p = Elastic modulus of UPVC (Plastic)
E_s = Elastic modulus of cob (soil)
a = Distance of neutral axis from extreme compression fibre
d = Depth of section

From the above equations (1–9), the induced stresses (tensile, compressive, and shear) were determined under factored loads and are presented in Tables 3 and 4 for wall types A and B, respectively. For the structural design checks in this study, the allowable strength parameters of cob were adopted from the 'New Zealand standard Engineering Design of Earth Buildings, NZS 4297:1998' [21] and 'A Review of Rammed Earth Construction'[22].

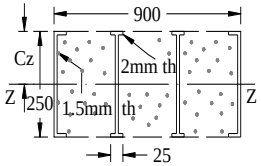
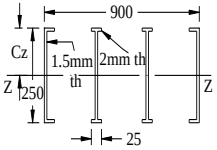
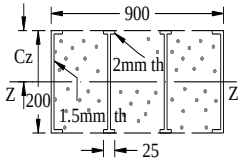
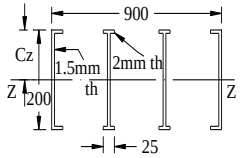
Based on the standard, the allowable strength parameters of cob are as follows:
Compressive strength: 0.50 MPa
Flexural (bending) strength: 0.10 MPa
Shear strength: 0.08 MPa
Modulus of Elasticity (E): 300 × fc (fc = compressive strength)
Direct tensile strength: Considered zero for design purposes.
The allowable strength parameters of UPVC are taken from the manufacturer specification and are as follows:
Compressive Strength: 60 MPa
Tensile strength: 45 MPa
Yield strength: 40 MPa
Flexural (bending) strength: 65 MPa
Shear strength: 20 MPa
Modulus of Elasticity (E): 3000 MPa

The design-checks, presented in tables 3 and 4, indicate that the proposed wall system satisfies strength and stability requirements under loading such as DL, LL, WL and EL. The design also demonstrates a favourable factor of safety, confirming the viability of the composite cob-UPVC wall for sustainable earthen wall in moderately seismic and wind prone regions.

The design checks (Sl. Nos. 3.2, 3.4, and 3.5 in table 3, and 4.2 in table 4) were also performed for the green (wet) state condition of the cob during construction, when the compressive load is carried solely by the vertical sheet (with rib). Under this condition, the horizontal sheet (with rib) (Sl. Nos. 3.5 in table 3 and 4.3 in table 4) supports the weight of the wet cob without any assistance from the underlying cob layer. A similar condition may also occur during subsequent repair works involving cob replacement.

Structural safety under applied loads was further evaluated by comparing the loads with the design strength capacities of the wall sections. Using the design strengths of cob and UPVC, the axial compression and bending moment capacities of the composite wall sections (900 mm × 250 mm and 900 mm × 200 mm) were computed and are presented in figures 39 and 40, respectively. The induced forces corresponding to the critical load combinations (1.5DL + 1.5WL, and, 1.5DL + 1.5LL) were also determined and plotted on the same graphs to assess the structural safety. The results indicate that the induced forces lie within the capacity envelopes, confirming that the composite wall sections are structurally adequate.

Table 3 – Preliminary structural design of wall type A (for sloped roof house)

Sl. No.	Member name	Section	Sectional properties	Critical load case	Factored force for design check	Stress check	Factor of Safety
Vertical Plate							
3.1	Vertical plate of Wall (from +0m to 1.75m)	 ***Fig. 32 -- Cob-UPVC composite section at bottom***	C/S area, A= 2.25x10^5 mm^2; Cob area, A_s =2.23x10^5 mm^2; UPVC area, A_p= 1876 mm^2; C_{zz}=125 mm.	1.5DL + 1.5WL (WL Load- case II)	At lev +0m: Bending Moment, M_Z= 1.5KN-m; Shear Force, F_y= 2.3 KN; Axial Force, F_x= 22.5KN(C)	σ_{cp} = 4.49 MPa (C) <60 MPa; σ_{tp} = 1.32 MPa (T) <40 MPa; σ_{cs} = 0.22 MPa <0.5 MPa; σ_{vs} (shear stress)= 0.01 MPa <0.08MPa.	2.27
				1.5DL + 1.5LL	At lev +0m: F_x =27.9KN(C)	σ_{cp} = 2.12 MPa (C) <60 MPa; σ_{cs} = 0.11 MPa (C) <0.5 MPa.	4.54
3.2		 ***Fig. 33 – UPVC section (without cob) at bottom***	A_p= 1876 mm^2; C_{zz}= 125 mm; I_{zz}= 13.59X10^6 mm^4; r_{zz}= 85 mm; r_{xx}= 3.4 mm.	1.0DL+ 1.0LL (During erection/ Repairing)	At lev +0m: F_x= 18.6KN(C)	From minimum slenderness ratio of whole member (height 3250 mm and r_{zz} 85 mm) and internal vertical plate (height 250 mm and r_{xx} 3.4 mm), Buckling strength = 11.37MPa σ_{cp} = 9.91MPa <11.37MPa;	1.14
3.3	Vertical plate of Wall (from +1.75m to +3.25m)	 ***Fig. 34 – Cob-UPVC composite section at top***	A= 1.80x10^5 mm^2; A_s= 1.78x10^5 mm^2; A_p= 1576 mm^2; C_{zz}= 100 mm.	1.5DL + 1.5WL (WL Load- case II)	At lev +1.75m: BM, M_z= 0.8KN-m; F_y= 0.3 KN; F_x=7.5 KN(C)	σ_{cp} = 3.52 MPa (C) <60 MPa; σ_{tp} = 3.74 MPa (T) <40 MPa; σ_{cs} = 0.18 MPa <0.5 MPa; σ_{vs} = 0.001 MPa <0.08 MPa	2.8
				1.5DL + 1.5LL	At lev +1.75m: F_x= 12.9KN(C)	σ_{cp} = 1.22 MPa (C) <60MPa; σ_{cs} = 0.06 MPa (C) <0.5MPa.	8.3
3.4		 ***Fig. 35 – UPVC section (without cob) at top***	A_p= 1576 mm^2; C_{zz}= 100 mm; I_{zz}= 7.68X10^6 mm^4; r_{zz}= 70 mm; r_{yy}= 3.65 mm (one vertical plate).	1.0DL+ 1.0LL (During erection/ Repairing)	At lev +1.75m: F_x= 8.6KN(C)	Buckling strength = 12.84 MPa; σ_{cp} = 5.46MPa <12.84MPa.	2.3

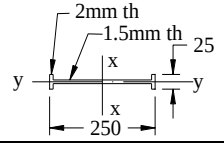
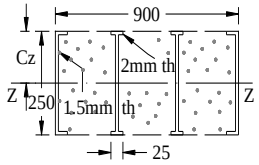
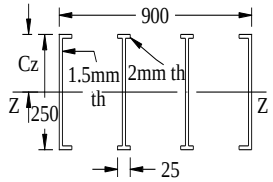
Sl. No.	Member name	Section	Sectional properties	Critical load case	Factored force for design check	Stress check	Factor of Safety
Horizontal Plate							
3.5	Horizontal plate	 *Fig. 36 – UPVC horizontal member*	Area (A)= 469 mm^2; C_{yy}= 12.5 mm; I_{yy}= 5277mm^4.	Self-weight of cob (erection stage)	M_y= 0.01 KN-m SF= 0.17 KN	σ_{cp}= 23.6MPa <40 MPa; σ_{tp}= 23.6MPa <60 MPa; σ_{vp}= 1.7MPa <20 MPa.	1.7
						Overall Factor of Safety = 1.14	

Table 4 – Preliminary Design of wall type B (for RCC house)

Sl. No.	Member name	Section	Sectional Properties	Critical Load Case	Factored Force for design check	Stress check	Factor of Safety
Vertical Plate							
4.1	Vertical plate of Wall (from +0m to 2.75m)	 *Fig. 37. Cob-UPVC composite section*	A= 2.25x10^5 mm^2; A_s= 2.23x10^5 mm^2; A_p= 1876 mm^2; C_{zz}= 125 mm.	1.5DL + 1.5WL (WL Load - case II)	At lev +1.5m: M_z= 1.23 KN-m; Axial Force, F_x =9.2 KN(C)	σ_{cp} = 3.58 MPa (C) <60MPa; σ_{tp} = 3.97 MPa (T) <40MPa; σ_{cs} = 0.17 MPa <0.5MPa.	2.94
				1.5DL + 1.5LL	At lev +0m: F_x= 18.3 KN(C)	σ_{cp} = 1.39 MPa (C) <60MPa; σ_{cs} = 0.07 MPa <0.5MPa.	7.14
4.2		 *Fig. 38. UPVC section (without cob)*	A_p= 1876 mm^2; C_{zz}= 125 mm; I_{zz}= 13.59X10^6 mm^4; r_{zz}= 85mm; r_{yy}= 3.4mm (one vertical plate).	1.0DL+ 1.0LL (During erection/ Repairing)	At lev +0m: F_x= 12.2 KN(C)	Buckling strength = 11.37MPa; σ_{cp} = 6.50MPa <11.37MPa.	1.74
4.3	**Horizontal Plate**: Same as 3.5, Table 3						
						Overall Factor of Safety = 1.74	

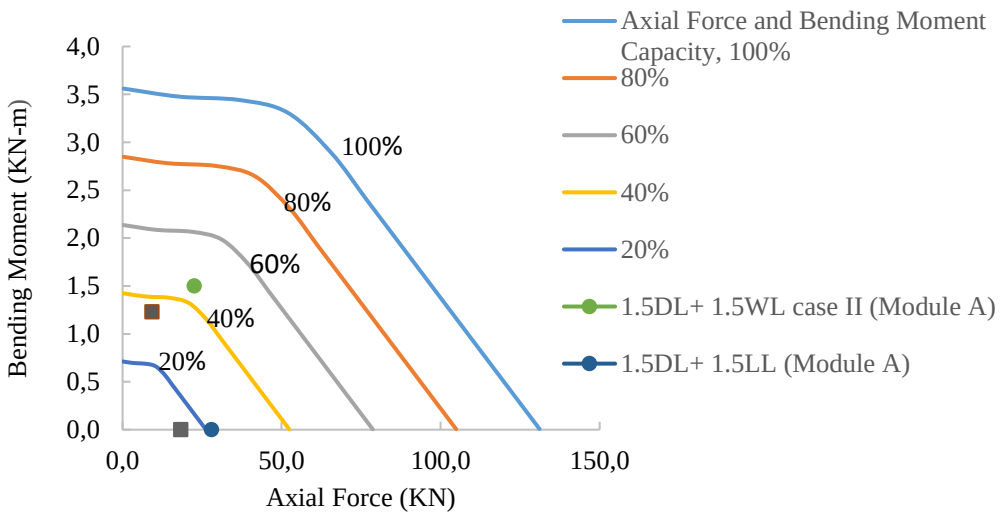


Fig. 39 – Axial compression and bending moment capacity of composite wall section- 900mm x 250mm

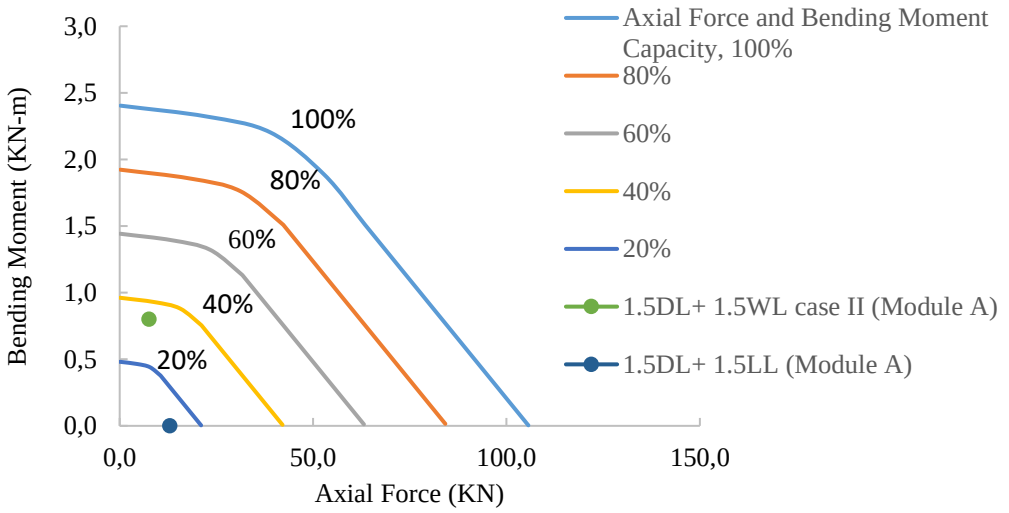


Fig. 40 – Axial compression and bending moment capacity of composite wall section- 900mm x 200mm

5 Discussion

The preliminary structural design of the cob-UPVC composite wall shows a promising alternative to conventional construction methods in terms of structural safety, affordability, sustainability and ease of construction. This section discusses the key findings of the proposed wall. Limitations and future scopes of work are also mentioned in the subsections.

The use of cob, a traditional earthen material, combined with a plastic (UPVC) frame reflects an innovative approach. Cob provides the compressive strength of the structure, prevents buckling of UPVC frame while UPVC member provides the necessary tensile strength and part of the compressive strength. As a composite structure, this technique may outclass the many existing techniques of constructing earth or mud wall.

The structural performance of the wall has been evaluated based on loading as per IS codes, with the permissible stress of cob taken from the New Zealand Standard Engineering Design of Earth Buildings, and that of UPVC based on manufacturer test data. Two wall types were assessed: type A for sloped roof houses and type B for RCC-framed houses.

In sloped-roof houses, Wall Type A functions as a load-bearing wall. Whereas, in RCC framed house, wall type B is intended as a non-load-bearing infill or partition wall. It can be used in single-storey to multi-storey buildings, provided that the RCC frame is designed to carry all structural loads (other than the local loads acting on the uPVC–cob wall). However, due to its relatively lower stiffness (compared to conventional brick masonry), limited composite interaction with the RCC frame, and maintenance challenges at higher elevations, its use as an external wall is suggested only up to limited heights (up to G+1) at this preliminary stage of the study.

Calculated stress ratios and factors of safety indicates that both wall types are structurally safe under DL, LL, WL and EL. The axial compressive capacity, derived from the combined compressive strength of cob and UPVC, is sufficient to withstand vertical loads like DL and LL. Design calculations show that the bending capacity contributed by the tensile strength of UPVC significantly enhances the composite section's ability to resist lateral loads such as WL and EL. Additionally, the tensile strength of UPVC and the self-weight of the cob contribute to resist the uplift due to wind. The proposed walls (type A & B) were evaluated for a basic wind speed of 47 m/s (169.2 km/h) and were found to be safe under this high wind speed. Overall, the composite behaviour of the wall ensures adequate resistance to the induced forces from all considered loading conditions.

A cost analysis was performed to compare the cost of the proposed wall system with that of traditional wall types. Based on prevailing market rates (near Delhi, India) and the Delhi Schedule of Rates (DSR 2023), the rough estimated cost (excluding contractor's profit and overhead charges) of the proposed mud wall for sloped roof houses (wall module A) is approximately Rs. 1360 per m², which is lower than the estimated cost of traditional cob wall. Since the construction costs of adobe block wall, pressed block wall, and rammed earth wall are higher than that of cob wall, the proposed mud wall is also more economical compared to these earth or mud walls. Furthermore, the estimated cost of wall module B is approximately Rs. 846 per m² (as per market rates and DSR 2023), which is significantly lower than the cost of 250 mm thick conventional brick masonry, estimated at about Rs. 2200 per m² (as per DSR 2023). These findings indicate that the proposed mud wall system is economically viable as a substitute for both traditional earth walls and brick walls, particularly in areas where suitable soil is locally available. Therefore, for low-cost housing in rural regions, the proposed system demonstrates considerable potential for practical application.

Apart from the stability and construction cost, another important advantage of the proposed wall is less construction time than the other earth walls. Another notable advantage is easy dismantling and reconstruction process. Durability is also expected to be better than the traditional cob wall. Like other earthen walls, proposed wall is more comfortable in terms of heat, breathability and humidity than the brick wall.

Despite these advantages, the proposed system has certain limitations. The primary limitation of this study lies in its theoretical nature- the design and analysis are based solely on analytical evaluation. Experimental validation is therefore essential to confirm the structural performance of the proposed configuration. Further studies are also required to assess the long-term composite behavior under various loading conditions and to evaluate the durability of UPVC over its service life.

Another limitation of the wall is its weakness in fire. Although UPVC is self-extinguishing and exhibits low combustibility, it begins to lose its mechanical strength at temperatures around 70-80°C. Consequently, during fire exposure, the structural strength of the wall in the affected region would depend solely on the cob component without any contribution from UPVC. To mitigate this concern, the exposure of UPVC elements can be minimized by embedding them deeper within the cob. This can be achieved by offsetting the exposed edge ribs by about 25 mm toward the wall center, resulting in a net wall thickness of 250 mm and an internal rib spacing of 200 mm. Such cob cover would offer a degree of thermal protection to the UPVC, thereby improving fire performance, although with a possible reduction in strength that should be quantified through detailed structural analysis.

The performance of the uPVC–mud wall system is also significantly influenced by environmental factors such as moisture, temperature variations, and solar exposure. Cob (mud) walls are inherently prone to moisture ingress, which can cause softening, erosion, and loss of strength under repeated wet–dry cycles. Furthermore, the mismatch in thermal expansion properties of uPVC and mud can generate interfacial stresses. However, provisions such as protective mud covering (25mm) and holes in the uPVC frame will prevent the moisture accumulation, while allowance for out-of-plane movement will help to relive the thermal stresses.

Overall, the integration of cob and UPVC in mud-wall construction shows a considerable potential in addressing the need for safe, sustainable and affordable housing. This preliminary design serves as a foundation for further investigation and field validation, and represents a step toward a new wall construction technique that align with socio-economic goals.

6 Conclusions

This study presents an innovative wall system that combines cob and rigid plastic (UPVC) to form a composite structural element aimed at enhancing the strength, stability, and cost-effectiveness in wall construction for low-cost housing. Two wall modules were considered- type A for sloped roofed mud houses and type B for RCC framed structures. Based on the conceptual arrangement and preliminary structural design of wall type A and B, the following conclusions are drawn:

- Preliminary structural design (based on BIS codes and NZS 4297:1998) confirms that both wall types are structurally stable under dead, live, wind, and earthquake loads. The inclusion of UPVC enhances tensile capacity and bending resistance, making the system a potential alternative to conventional mud walls and brick infill walls.
- Estimated cost analysis indicates that the proposed wall system is more economical than traditional earthen wall types (e.g., cob, adobe, rammed earth, and pressed block walls), primarily due to reduced consumption of concrete, mud and labour in spite of additional cost of UPVC. Compare to the conventional brick wall (250 mm thick), the proposed wall is approximately 62% cheaper.
- The modular configuration allows faster construction, easier dismantling, and reinstallation. Similar to other earthen systems, the wall promotes sustainability and provides better thermal comfort, contributing to improved indoor livability.

Overall, the proposed cob–UPVC composite wall demonstrates strong potential in earthen wall construction for sustainable and affordable housing. However, further experimental validation is required to confirm its practical performance under real conditions.

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