MUD-CONCRETE SLAB SYSTEM FOR SUSTAINABLE CONSTRUCTION

JAYASINGHE R.R.[1], NANAYAKKARA K.I.U.[2], AROOZ F.R[3] & HALWATURA R.U.[4]
[1, 4]Department of Civil and Engineering, Faculty of Engineering, University of Moratuwa, Katubedda, Sri Lanka
[2]Department of Civil and Structural Engineering, Faculty of Engineering, The University of Sheffield, Sheffield, United Kingdom
[3]Department of Architecture, General Sir John Kotelawala Defence University, Sewanagala, Sri Lanka
[1]rohantharukshan@gmail.com, jayasingherr.19@uom.lk [2]kiunanayakkara1@sheffield.ac.uk,
[3]frarooz@kdu.ac.lk, [4]rangika@uom.lk

Abstract: The urgency of global climate emergency has drawn significant attention to the building industry over the last few years. Today, the building sector is responsible for 38% of the world's greenhouse gas emissions, according to UNEP. 60% -70% of embodied carbon in a conventional column-beam reinforced concrete building is in its floor system. This paper discusses the possibility of constructing an earthen slab system using mud-concrete. It investigates a doubly curved shell structure, working predominantly in compression, to fulfil both environmental and economical demands in the construction industry; reducing the cost and labour expenses nearly 50% compared with that of traditional reinforced concrete slab systems. A 1 m x 1 m prototype mud-concrete slab was constructed to check the potential for modular construction with a square footprint. Poured mud-concrete shell of 50 mm thickness is the primary structural component, while a non-structural mud-concrete filling to a horizontal level 50 mm from apex was used to create a usable floor surface. Masonry mould method was used as the formwork system for the construction considering its cost effectiveness and ease of construction.

Keywords: *Doubly-curved shells, Compression-only Structures, Mud-Concrete, Earthen Slabs, Thin shells*

1. Introduction

Construction industry causes substantial environmental damage by its greenhouse gas emissions into the earth's atmosphere (Ahmed et al., 2021) and is the primary contributor of energy related CO_2 emissions (UNEP, 2020). By 2050, two-thirds of the global population would be urban and sustainable development would not be achieved without significantly changing or improving the current methods of construction technologies (UNEP, 2020). Therefore, a sustainable approach to the building design process is considered to be of prime importance for the construction industry to move towards its goal of zero-carbon construction practices.

As the world population increases rapidly, the stock of natural resources has been depleting exponentially. Although policies for sustainable construction and demolition waste management have been adopted across the world, still construction and demolition waste accounts for up 30-40% of the total solid waste generated, much of it heading to landfills untreated and thus causing environmental and socio-economic problems (Islam et al., 2019; Menegaki and Damigos, 2018). To address the current crisis in the construction industry, sustainable building materials (e.g: Bamboo, wood, soil, etc.) are being trialled. Earth, one of the oldest construction materials—dating back to the period of El-Obeid in Mesopotamia 5000-4000 BC (Pollock, 1999)—can still be used as a sustainable building material in the modern construction industry. The popularity of earthen construction material has declined due to industrialization in the 18th century (Patnaik, 2018). However, due to the rising demand for affordable and sustainable housing, various earthen construction technologies and practices have resurfaced in recent years and building with earth has become a global trend in both the developed and developing world.

DOI: https://doi.org/10.31705/FARU.2021.27

There are many earthen construction technologies and practices available for walling systems, such as Compressed and Stabilized Earth Block (CSEB) walls (Maïni, 2005; Malkanthi et al., 2020) rammed earth walls (Koutous and Hilali, 2021; Walker et al., 2005) and mud concrete walls (Arooz, 2019). However, most of the current earthen constructions are restricted to either single storey buildings or use conventional slab systems—reinforced concrete slab systems, pre-cast floor slabs, composite floor slab—along with earthen walling systems. 60% -70% of embodied energy in a conventional column-beam reinforced concrete building is its floor system (Foraboschi et al., 2014). Thus, an earthen slab system would be a significant step towards a zero-carbon house.

Tensile capacity of earthen materials is comparatively low compared to conventional reinforced concrete. Thus, it is not possible to create a typical flat slab system using only earthen materials. Ockleston stated that "Restraining flat slabs laterally could increase their loading capacity by almost three times due to an arching effect known as compressive membrane action" (Ockleston, 1958). Hence, the structural efficiency could be increased through the arching effect. If an alternative slab system is to be designed with a significant arching effect, it could reduce the self-weight of the structure in a similar order of magnitude. One of the possible earthen slab systems identified was Catalan vault-inspired earthen slab system (Jayasinghe et al., 2019; Ochsendorf, 2010), which uses thin tiles to build the shell while non-structural filling is used as a ballast to set it as a floor. However, there are several problems that arise when adopting thin shell tile vaulting to Sri Lanka, including issues in material quality and seismic capacity. As a solution, a singly curved shell structure was developed using mud-concrete (Rathnayake et al., 2021). Doubly curved shells a rigid and more stable structures, improving upon deficiencies of its singly curved counterpart.

Mud-Concrete is a concrete material which uses soil as its primary binding material. Mud-concrete deviates from typical concrete mixture by replacing sand and granite coarse aggregates with a graded soil. When mud-concrete is used as a walling material, initial cost and operational cost is comparatively low compared with that of cement brick or burned bricks walls (Udawattha and Halwatura, 2016, 2017). Furthermore, the environmental impact of the mud-concrete is significantly low compared with other building materials. 92% of mud-concrete elements can be recycled and reused by crushing and producing new mud-concrete elements (Udawattha and Halwatura, 2017).

This paper presents the possibility of developing a doubly curved earthen slab system using mud-concrete to achieve demands of economy, environment and aesthetics.

2. Objectives

The work presented in this paper is broadly aimed towards developing an earthen slab system for housing in Sri Lanka. The main objectives of this research are to;

- Propose a feasible structural system for an earthen slab system
- Develop a practical construction sequence for the proposed slab system
- Evaluate economic and environmental viability of the proposed slab system

3. Structural Form

3.1. FORM AND FORM DEVELOPMENT

Typically, shell structures are lightweight structures which gain their rigidity through its curved forms. According to the curvature, shells can be defined as (i) flat, (ii) singly-curved, (iii) conically shaped, (iv) doubly-curved-synclastic, (v) doubly-curved-anticlastic and (vi) freeform surface (see Figure 1). Since geometric stiffness of doubly curved shells are higher than singly curved shells or flat surfaces, for the proposed slab system, a doubly-curved shell was selected. There are two types of doubly curved shapes, as mentioned above; (i) anticlastic surfaces, also known as saddle shape, and (ii) synclastic shapes, also known

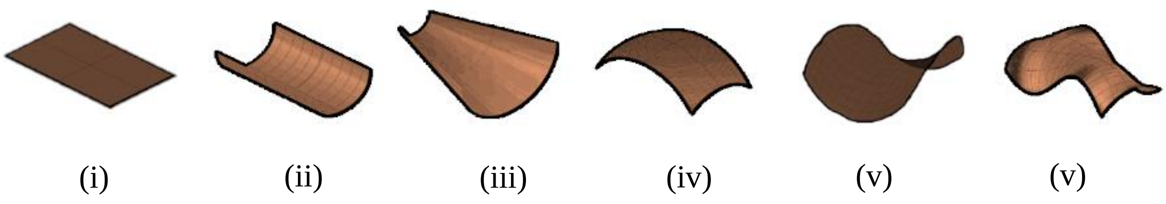


Figure 1: Surface topology; (i) flat, (ii) singly-curved, (iii) conically shaped, (iv-1) doubly-curved-synclastic, (iv-2) doubly-curved-anticlastic and (v) freeform surface

as dome shaped. Although, both surfaces are stable and stiffer designs, doubly curved synclastic shape was selected by considering absence of tension.

The proposed slab system consists of two main components; a thin shell working as the primary structural component and a non-structural filling contributing as ballast loading. The shell structure is a thin, curved compression-only structure that performs well under external loading. The ballast is primarily to create a flat surface for the floor, but it also contributes to the structural robustness of the system by reducing the impact of variable loading on the floor.

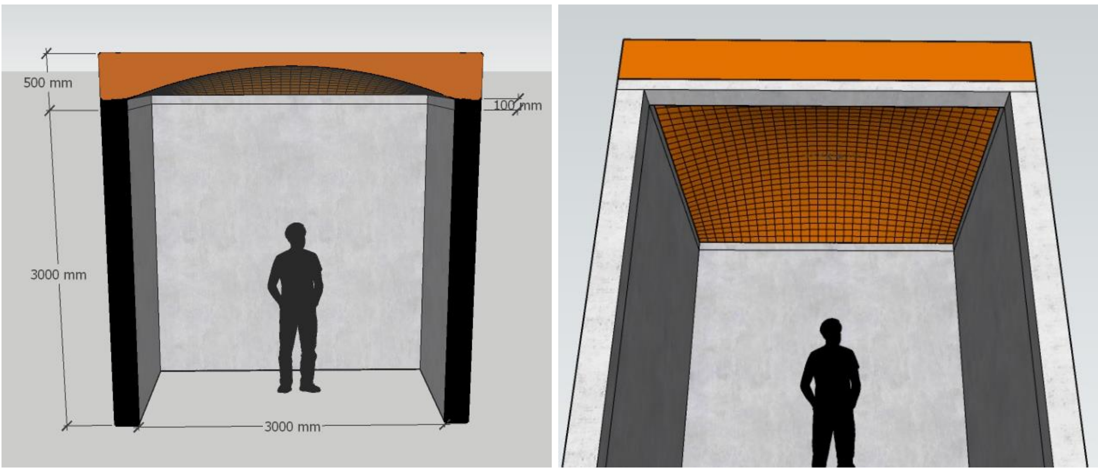
The doubly curved geometry is chosen such that the structure would act predominantly in compression. The earthen material is capable of carrying a minimal amount of tensile stresses generated. Thus, the requirement of reinforcement is completely eliminated. The prototype testing will be used to check if there would be non-structural causes requiring addition of reinforcement.

3.2. SELECTING SIZE AND SHAPE FOR THE SHELL

For a typical urban or sub-urban dwelling unit in Sri Lanka, column to column distance or wall to wall distance of 3m is taken as representative. Thus, for the doubly curved shell structure:

- 3 m x 3 m square footprint was selected
- Rise of the shell was considered as L/10 where L equals to span
- The thickness of the shell was taken as 50 mm
- For the ballast loading, the surface level was considered as 50 mm from the apex

Thickness for the shell and the level of the ballast was taken by considering the maximum aggregate size of the mud-concrete mixture. Figure shows the cross-section of the proposed structure.



(i) (ii)

Figure 2: (i) cross-section and (ii) perspective view of the proposed slab system

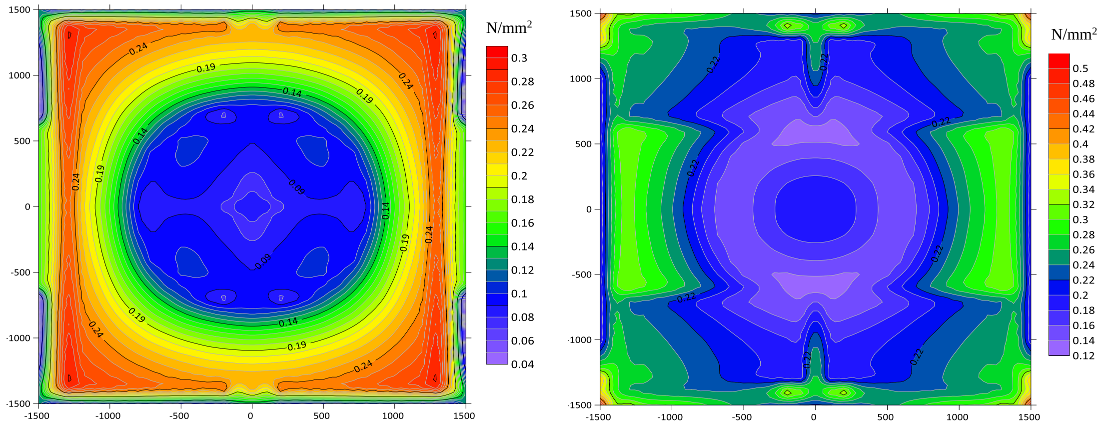
3.3. STRUCTURAL ANALYSIS

Structural analysis was carried out using linear-elastic Finite Element Modelling (FEM), using SAP2000 software package, to find maximum (tensile) and minimum (compressive) stress distribution of the proposed design—see Figure 3.

In accordance with BS-EN-1991-1, the shell was investigated under a concentrated and distributed live loading. First, a 2kN concentrated loading was applied as live loading for a slab system. The shell was meshed into 100 mm x 100 mm grids and the concentrated point load was applied at each grid point, one at a time. The critical condition was when the concentrated load was applied at 1838.48 mm from the centre of the vault (coordinates of [1300,1300], or its symmetric counterparts). In that critical placement of the concentrated load, the critical stresses occurred at the bottom surface of the shell structure. The maximum tensile stress observed for the concentrated point loading was 0.291 N/mm^2 and the maximum compressive stress was 0.498 N/mm^2.

Thereafter, a 2kN/m^2 uniformly distributed load (UDL) was applied, considering five loading patterns using quadrant loading. Critical loading condition for the UDL loads was when the loading was applied over half of the vault, and the corresponding maximum tensile stress was 0.094 N/mm^2 and maximum compressive stress was 0.232N/mm^2.

Thus, concentrated loading condition is found to be the most critical loading condition for the design. Also, these values are within the strength of mud concrete, which were found to be varying between 3.0-3.3 N/mm^2 and 0.3-0.33N/mm^2 for compression and tension respectively. Figure 3 shows the maximum tensile stress distribution and maximum compressive stress distribution at the critical placement of the concentrated load of 2kN. In any case, development of tensile stresses in the vault section will not cause a total collapse of the structure: That would require cracks across full thickness of the shell forming an admissible collapse mechanism. Onset of tensile cracking only indicates a lower bound estimate of the collapse load.



(i) (ii)

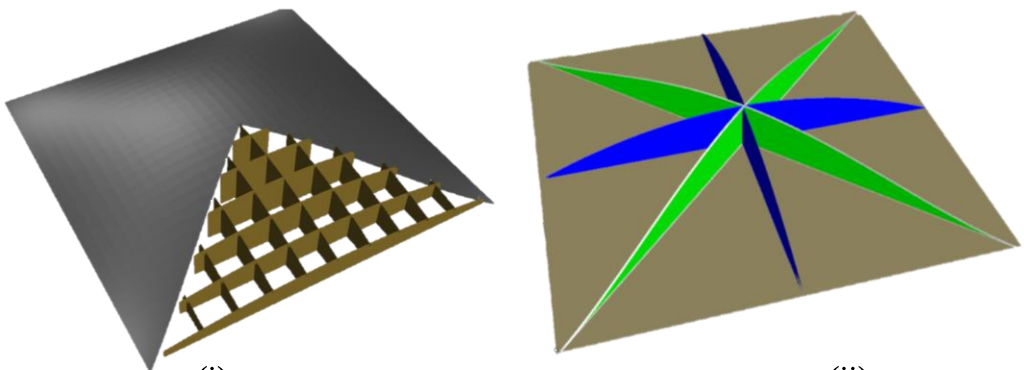
Figure 3: (i) Maximum tensile stress distribution of the bottom surface and (ii) Maximum compressive stress distribution of the bottom surface, at the critical placement of the concentrated load of 2kN applied on the flat surface of the vault section

4. Construction

To investigate the viability of the proposed mud-concrete slab system, a 1 m x 1 m prototype was constructed.

4.1 FORMWORK DESIGN

Rhinoceros 3D software package with Grasshopper add-on was used for the design of formwork. Initially, two possible formworks were identified; (i) waffle type steel formwork, which could be constructed with laser-cut steel plates (see Figure 4i), and (ii) a plywood formwork, to construct a masonry cement mould (see Figure 4ii).



(i) (ii)

Figure 4: (i) Waffle type steel formwork and (ii) Plywood framework to construct the masonry cement mould (Software: Rhinoceros 3D)

4.2. PREPARATION OF MUD-CONCRETE MIX

The soil was air-dried, sieved and mixed to obtain the desired particle size distribution. As Arooz (2019) notes, compressive strength of the mud-concrete mixture would reduce with increasing water content. Therefore, to maintain the water content in the mixture, a water reducing admixture was used. The mud-concrete mixture was prepared in two separate batches; one for the shell and the other for the ballast. First, dry aggregates and cement were mixed thoroughly with 60% of the total water requirement. Thereafter, water-reducing admixture (1% by weight of cementitious materials) was added to the damped mixture to reduce segregation and to improve the workability of the mixture. The mud concrete mix design for the proposed design is as shown in Table 1.

Soil Proportions	Fine (≤ Sieve size 0.425mm)	5%
	Sand (Sieve size 0.425mm ≤ Sand ≤ 4.75mm)	50%
	Gravel (Sieve size 4.75mm ≤ Gravel ≤ 32mm)	45%
Cement	Minimum cement from the total sample weight	4%
Water	Water from dry mix	20%

Table 1: mud-concrete mix design for the proposed design (arooz, 2019)

4.3. CONSTRUCTION SEQUENCE

After constructing the side walls (height of 1m) and edge beams (size of 150mm x100mm) (see Figure 6i), plywood formwork was placed and fixed with struts—at bottom of the struts, two opposing wedges were placed to decentre the formwork after casting (see Figure 6ii and 6iii). Plywood framework as discussed in Section 4.1 was used to achieve the desired doubly-curved shape. Using cement sand mortar, masonry mould was casted for the prototype built (see Figure 6iv), considering this to be a one-off build. Steel formwork may be preferred in modular construction with multiple usage.

After fixing sideboards and supports, mud-concrete mixture was poured in two stages: 50 mm thick shell and filling up to 50mm from shell apex. Gauge rod was used to maintain the shell thickness to 50 mm. In this stage, it is vital to keep the water content as mention in Table 1. Mud-concrete mixture should not be too dry (may form honeycombs) or too runny mixture (may result in segregation). After completing the shell, mud-concrete mixture was poured as the non-structural ballast. Same mixture was used for the both shell and ballast. However, it was cast as two segments, so that there is a construction joint between both parts. The construction sequence for the construction of doubly curved shell structure is explained in Figures 5 and 6 and the completed earthen slab system and intrados surface of the shell is shown in the Figure 7.

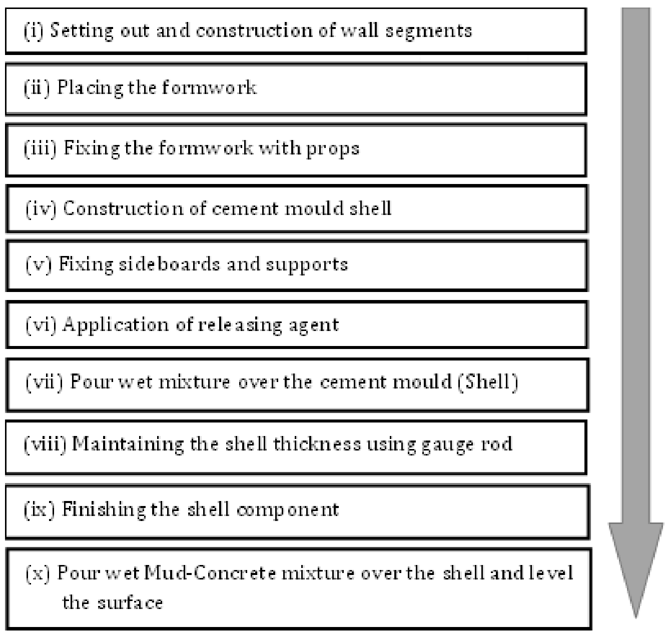


Figure 5: Flowchart of the construction sequence

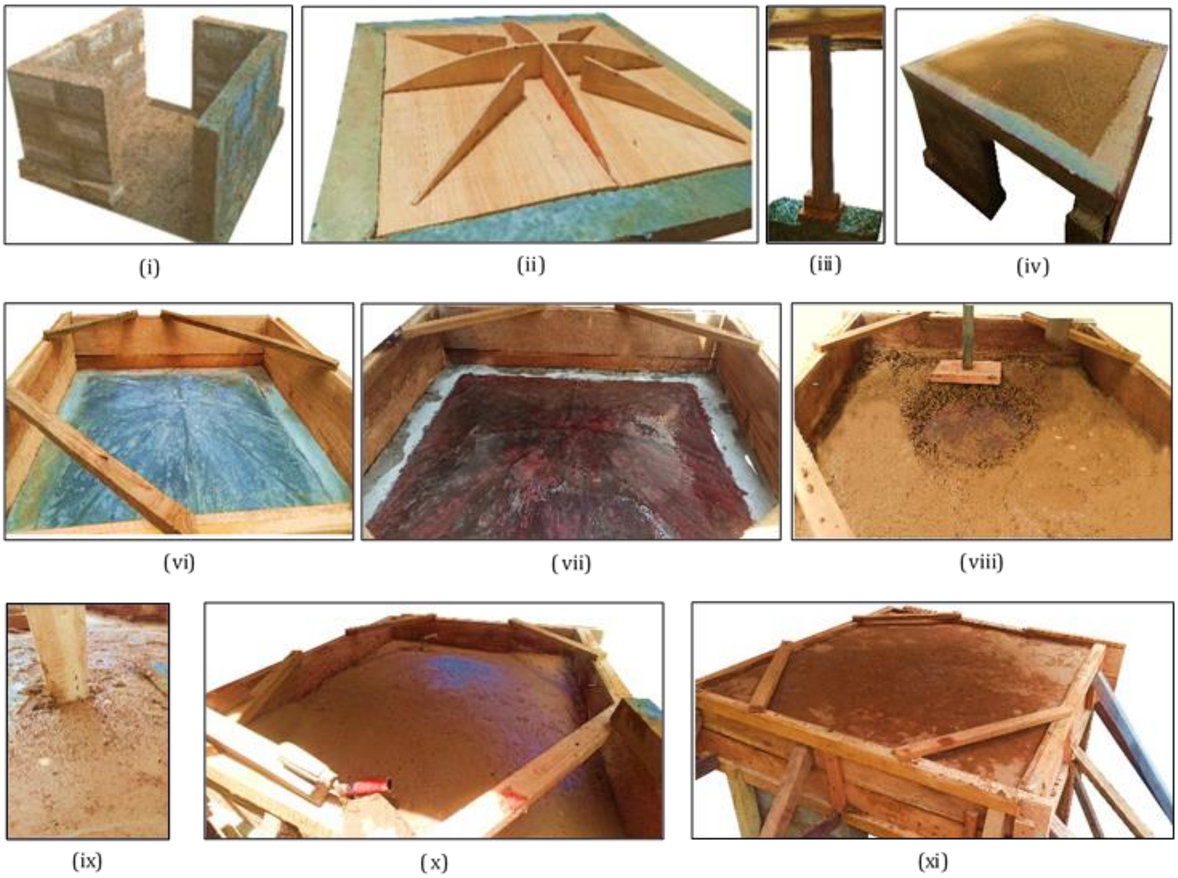
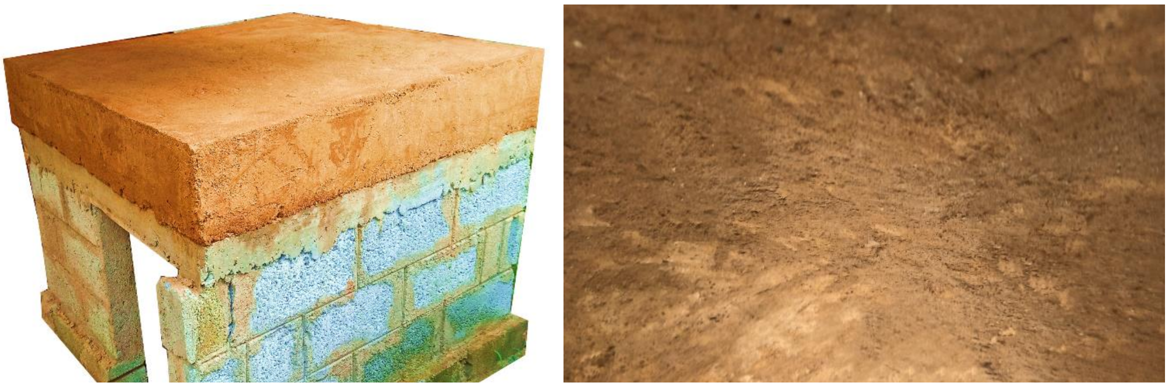


Figure 6: Construction sequence of the construction



(i) (ii)

Figure 7: (i) Completed earthen thin shell slab system and (ii) intrados surface of the shell.

5. Cost Comparison and Embodied Energy Calculation

Construction cost and embodied energy was calculated for three different slab systems, for a 3m x 3m footprint; (i) typical reinforced concrete slab; (ii) doubly curved earthen slab system; and (iii) a concrete slab system for the same structural form. A nominal thickness of 150mm was considered for the typical reinforced concrete slab system. 1m x 1m model, which was constructed previously, was used to estimate the total cost for a 3m x 3m earthen slab system. All the rates were calculated from Building Schedule of Rates (BSR-2019/2020) and according to CIDA regulations in Sri Lanka. Thus, labour cost is calculated on daily-work basis of skilled and unskilled labour force. Cost summarization for three different slab systems is shown in Table 2.

For embodied energy calculations, required soil volume was taken as 4.56 m^3 and no energy was required for manual excavation of soil. Also, according to the local regulations, 25 km of hauling distance was considered for the soil transportation and for the cement transportation it was taken as 50 km (Fay and Raniga, 2000; Jayasinghe, 2011). Embodied energy calculations for three different slab systems are as shown in Table 3.

	Traditional R.C.C. Slab system	**Doubly curved shell with earthen materials**	**Doubly curved shell with concrete**
	Amount (LKR)	Amount (LKR)	Amount (LKR)
Material Cost			
Filling material	596.86	148.00	638.64
Reinforcement	308.56	-	-
Formwork	281.00	343.50	343.50
Labour cost	191.77	224.79	148.59
Total cost per sq.ft	1378.19	716.29	1130.73
Cost reduction	-	**48%**	**18%**

Table 2: Cost summarization for three different slab systems

Traditional R.C.C. Slab system				
Material	Unit	Qty.	Energy per unit in MJ	Embodied Energy in MJ
Reinforced concrete slab	m^2	9	730	6570
Formwork material				
Plywood	Kg	70.2	15	1053
Total EE				**7623.00**
Doubly curved shell with earthen materials				
Material	Unit	Qty.	Energy per unit in MJ	Embodied Energy in MJ
Soil (Transport)	m^3	4.56	43.75	199.5
Cement	Kg	200	5.85	1170
Transport	Ton.	0.2	50	10
Formwork material				
Plywood	Kg	108.7	15	1630.5
Cement sand mortar	m^3	1.2	773	927.6
Total EE				**3937.60**
Doubly curved shell with concrete				
Material	Unit	Qty.	Energy per unit in MJ	Embodied Energy in MJ
Concrete 1:2:4	m^3	2.4	1664	3993.6
Formwork material				
Plywood	m^3	0.167	8520	1422.84
Cement sand mortar	m^3	1.2	773	927.6
Total EE				**6344.04**

Table 3: Embodied energy calculations for three different slab systems

6. Discussion

Material cost was separated into two parts, as shown in Table 2; filling material and reinforcements. It is clear that the 48% cost reduction in the earthen slab system is primarily from the filling material. Similar trend is observed in the embodied energy. This amount may be further reduced when the earthen material is freely available from excavations for substructure or other means. Further opportunities for cost reduction are present in the formwork system. An improved formwork system which is reusable along with modular construction can spread out the formwork cost among multiple earthen shell slabs. This need for an improved formwork system is further noted in plywood used for the formwork contribution to more than 40% of the total embodied energy of the earthen slab system.

Both the structural shell and the ballast of the slab designed and built in this paper is of the same density. There is the possibility to reduce the self-weight by using aerated mud-Concrete for the ballast, although the environmental performance of the aerating compound needs to be further assessed. This reduced self-weight would allow the rest of the structure carrying the slab—e.g. walls and foundation—to be reduced in size. A more prudent approach to improving the effectiveness of the ballast would be by incorporating construction demolition waste in the ballast. This is a traditional practise with Catalan thin tile vaults in Catalonia region in Spain.

Although the doubly curved shape in earthen slab system is used to achieve a structure predominantly in compression that too contributes to cost and embodied energy reduction. This is specifically noted in terms of embodied energy where the reduced material usage cutting down material related embodied energy by 40%. This strategy of doubly curved concrete shells in modular construction have been previously studies (Hawkins et al., 2020). Current study did not look into optimizing the doubly curved geometry. This provides an opportunity for the proposed system to be further improved.

Labour cost of the earthen shell is slightly higher than the reinforced concrete slab system due to the labour-intensive soil sieving process. This may also impact the programming of the construction work. But such costs are likely to go down as novel technologies get widely adopted. Another effect of high labour intense novel materials and construction procedures is in the programming sequence. Until further researches are available to cut down on curing period and formwork/falsework removal times, a careful approach with testing where possible is suggested.

Furthermore, the proposed slab system has interesting visual features. The domed interior gives an enhanced perception of space and a smoothened edge at the connection to the wall may enhance this. It was also observed that the surface texture of the constructed slab system has a pleasing smooth yellowish-brown earthy texture. A transparent protective coating will retain this visual effect while improving the durability of the earthen shell.

7. Conclusions

The work presented in the paper supports the proposal of using an earthen slab of doubly-curved form to achieve improved economic and environmental performance. The analysis leads to other important aspects of this technique regarding strength of the slab system, and further opportunities to improve and refine the proposed system. The key findings from the study are concluded as follows;

1. A doubly curved mud-concrete slab systems, with a 50mm thick shell and 50mm filling from apex for ballast loading, is capable of safely carrying its design load.
2. A 48% cost and embodied energy reduction is observed for the 1m x 1m prototype slab, compared with the traditional reinforced concrete slab systems.

8. Acknowledgment

This material is based on work supported by the SRC (Senate Research Committee Grant, University of Moratuwa) Grant Number- SRC/ST/2020/02 and the authors would like to acknowledge the support given by the technical officer, Ms.W.B.U. Rukma from Department of Civil Engineering, University of Moratuwa.

9. References

Ahmed, N., Abdel-Hamid, M., Abd El-Razik, M.M., El-Dash, K.M., 2021. Impact of sustainable design in the construction sector on climate change. Ain Shams Eng. J. 12, 1375–1383. https://doi.org/10.1016/J.ASEJ.2020.11.002

Arooz, R., 2019. In-situ Mud-Concrete as a material for load-bearing walls and sustainable building practices.

Fay, R., Raniga, U.I., 2000. Life-cycle energy analysis of buildings: A case study. Build. Res. Inf. 28, 31–41. https://doi.org/10.1080/096132100369073

Foraboschi, P., Mercanzin, M., Trabucco, D., 2014. Sustainable structural design of tall buildings based on embodied energy. Energy Build. 68, 254–269. https://doi.org/10.1016/j.enbuild.2013.09.003

Hawkins, W., Orr, J., Ibell, T., Shepherd, P., 2020. A design methodology to reduce the embodied carbon of concrete buildings using thin-shell floors. Eng. Struct. 207, 110195. https://doi.org/10.1016/J.ENGSTRUCT.2020.110195

Islam, R., Nazifa, T.H., Yuniarto, A., Shanawaz Uddin, A.S.M., Salmiati, S., Shahid, S., 2019. An empirical study of construction and demolition waste generation and implication of recycling. Waste Manag. 95, 10–21. https://doi.org/10.1016/J.WASMAN.2019.05.049

Jayasinghe, C., 2011. Embodied energy of alternative building materials and their impact on life cycle cost parameters. Int. Conf. Struct. Eng. Constr. Manag. December 16-18, 2011, Kandy, Sri Lanka 1–20. https://doi.org/10.13140/RG.2.1.4852.2321

Jayasinghe, R.R., Nanayakkara, K.I.., Arooz, F.R., Halwatura, R.U., 2019. Catalan Vault Inspired Earthen Slab System for Houses in Sri Lanka: Form-Finding.

Koutous, A., Hilali, E., 2021. Reinforcing rammed earth with plant fibers: A case study. Case Stud. Constr. Mater. 14, e00514. https://doi.org/10.1016/J.CSCM.2021.E00514

Maïni, S., 2005. Earthen architecture for sustainable habitat compressed stabilised earth block technology. High Commission ofRyadh City Development. The Auroville Earth Institute, Auroville Building Centre INDIA.

Malkanthi, S.N., Balthazaar, N., Perera, A.A.D.A.J., 2020. Lime stabilization for compressed stabilized earth blocks with reduced clay and silt. Case Stud. Constr. Mater. 12, e00326. https://doi.org/10.1016/J.CSCM.2019.E00326

Menegaki, M., Damigos, D., 2018. A review on current situation and challenges of construction and demolition waste management. Curr. Opin. Green Sustain. Chem. 13, 8–15. https://doi.org/10.1016/J.COGSC.2018.02.010

Ochsendorf, J., 2010. Guastavino Vaulting: The Art Of Structural Tile. Princeton Architectural Press, Princeton, NJ.

Ockleston, A.J., 1958. Loading tests on reinforced concrete slabs spanning in two directions. Portland Cement Institute.

Patnaik, R., 2018. Impact of Industrialization on Environment and Sustainable Solutions - Reflections from a South Indian Region, in: IOP Conference Series: Earth and Environmental Science. Institute of Physics Publishing, p. 12016. https://doi.org/10.1088/1755-1315/120/1/012016

Pollock, S., 1999. Ancient Mesopotamia [WWW Document]. URL https://books.google.lk/books/about/Ancient_Mesopotamia.html?id=ndjc_5xhlDsC&redir_esc=y (accessed 6.10.21).

Rathnayake, R.M.., Jayasinghe, R.R., Nanayakkara, K.I.U., Arooz, R., Halwatura, R.U., 2021. Developing singly-curved earthen slab system for houses using mud-concrete, in: 8th International Symposium on Advances in Civil and Environmental Engineering Practices for Sustainable Development. Hapugala, Galle Sri Lanka, pp. 214–220.

Udawattha, C. and, Halwatura, R., 2016. The embodied energy and life cycle costing: A case study on basic dwellings in Sri Lanka. Natl. Green Conf. 2016 Univ. Kelaniya 18, 1–10.

Udawattha, C., Halwatura, R., 2017. Life cycle cost of different Walling material used for affordable housing in tropics. Case Stud. Constr. Mater. 7, 15–29. https://doi.org/10.1016/j.cscm.2017.04.005

UNEP, 2020. Sustainable Development Goals (SDGs) and Disability [WWW Document]. URL https://www.un.org/development/desa/disabilities/about-us/sustainable-development-goals-sdgs-and-disability.html (accessed 10.29.21).

Walker, P., Keable, R., Martin, J., Maniatidis, V., 2005. Rammed earth: design and construction guidelines. Watford: BRE.