

FEASIBILITY ANALYSIS OF INTERLOCKING DRY BLOCK CONSTRUCTION - A SUSTAINABLE STEP TOWARDS DESIGN FOR DECONSTRUCTION

A Thesis

Submitted in partial fulfillment of the requirements for the award of
Master of Architecture degree in Building Management

by

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SCHOOL OF BUILDING AND ENVIRONMENT**

SATHYABAMA

**INSTITUTE OF SCIENCE AND TECHNOLOGY
(DEEMED TO BE UNIVERSITY)**

Accredited with Grade "A" by NAAC

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MAY 2021



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BONAFIDE CERTIFICATE

This is to certify that this Report is the bonafide work of **SWATHI LAKSHMI M (39840019)** who carried out the Thesis entitled "**FEASIBILITY ANALYSIS OF INTERLOCKING DRY BLOCK CONSTRUCTION - A SUSTAINABLE STEP TOWARDS DESIGN FOR DECONSTRUCTION**" under our supervision from January 2021 to May 2021.

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ACKNOWLEDGEMENT

I am pleased to acknowledge my sincere thanks to Board of Management of **SATHYABAMA** for their kind encouragement in doing this Thesis project and for completing it successfully. I am grateful to them.

I convey my thanks to **Dr. Devyani Gangopadhyay, Dean and Head of the department, Dept. of Architecture, School of Building and Environment**, for providing me necessary support and details at the right time during the progressive reviews.

My special thanks to **Dr. Suresh Kuppusamy**, our Design chair and **Mr. S. Kavin Kumar, Director, EPMCR**, (External guide) and **Ar. Sukirtha Suresh** (Thesis Coordinator) for their valuable comments and orientation during the project work.

I would like to express my sincere and deep sense of gratitude to my Project Guide **Ar. Sukirtha Suresh** for her valuable guidance, suggestions and constant encouragement which paved way for the successful completion of my project work.

I wish to express my thanks to all Teaching and Non-teaching staff members of the Department of Architecture who were helpful in many ways for the completion of this Thesis.

ABSTRACT

Design for deconstruction is one of the key principles of circular economy as per UKGBK, 2019. There is a dire need for circular economy principles to be implemented in the Indian construction industry as the Indian construction sector is towards rapid growth rate and it has to be guided with circular economy principles to lead the development towards sustainable growth.

The demolition and modification of the building generate huge amount of waste which end up in the landfill and put pressure on the raw material extraction for manufacture of new building materials. To solve this issue and to ensure waste reduction and material and resource conservation, the building shall be designed in the initial stage for its deconstruction methodology. The materials and construction technology that are chosen should cater to the needs of efficient deconstruction.

Using Interlocking earth block works shall benefit the design for deconstruction as they are individual modular units that are dry stacked one above the other to create walls and columns and can be removed easily without damage of the materials.

In the project, the framework for construction and de-construction of interlocking dry earth block construction shall be derived and quality checklists and procedure checklists shall be framed to cater to the efficient dismantling of the structural elements and obtaining the material back without defects.

Along with the framing of construction and de-construction manual, the potentials and benefits of the interlocking dry earth blocks are also analysed under various categories. The impact of the interlocking dry earth blocks on circular economy and sustainability are studied.

Keywords: *Circular Economy, Interlocking Block, Dry stacking blocks, Mortarless Construction, Interlocking Stabilized Soil Block, Design for Deconstruction, Flexible Construction, Closing the loop.*

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LIST OF SYMBOLS AND ABBREVIATIONS

MPa	-	Mega Pascal
CE	-	Circular Economy
DfD	-	Design for Deconstruction
ISSB	-	Interlocking Stabilised Soil Block
HUDCO	-	Housing and Urban Development Corporation
RW	-	Weighted Sound Reduction Index
pcf	-	Pounds per Cubic Foot
BTU	-	British Thermal Unit
UK-GBC	-	United Kingdom - Green Building Council
SDG	-	Sustainable Development Goal
MoHUA	-	Ministry of Housing and Urban Affairs
GDP	-	Gross Domestic Product
NSDC	-	National Skill Development Corporation
CDW	-	Construction and Demolition Waste
IGBC	-	India Green Building Council
LIG	-	Low Income Group
MIG	-	Middle Income Group
EWS	-	Economically Weaker Section
AAC	-	Autoclaved Aerated Concrete
CMWSSB	-	Chennai Metrowater Supply and Sewerage Board
IDEB	-	Interlocking Dry Earth Block
TISTR	-	Thailand Institute of Scientific and Technological Research

HSD-AIT	-	Human Settlements Division of the Asian Institute of Technology
N	-	Newton
Ksc	-	Kilograms per Square Centimetre
Psi	-	Pounds per Square Inch
RCC	-	Reinforced Cement Concrete
IIT	-	Indian Institute of Technology
BIS	-	Bureau of Indian Standards
CSEB	-	Compressed Stabilised Earth Block
EVV	-	Embodied Energy Value
LEED	-	Leadership in Energy and Environment Design
MEP	-	Mechanical, Electrical and Plumbing
SEDA	-	Scottish Ecological Design Association

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Housing is one of the fundamental need of humanity, third behind food and water. The shelter of the human being should cater to the need and comfort of the person. The housing should be adaptable and flexible to human needs. A residential building for a family is in need of redesign and modification to fit to the need of growing family. The demolition of buildings, either full building or part of building is becomes necessary to adapt to the growing or new user demands. This leads to wastage of building materials, labour, cost and other resources. In today's world, there is a dire need for sustainable development and reduce resource extraction. The conservation of natural resource shall be achieved by closing the loop of the building materials and reusing the materials instead of dumping them in landfills.

The construction and demolition waste shall be reduced by reducing the demolition of building itself. The demolition of building must be replaced by deconstruction of building so that the building elements can be reused readily. The conventional building system must be replaced with new technology that is fit for easy deconstruction.

The interlocking dry earth blocks will be an appropriate replacement for the traditional masonry brick walls as they're flexible and might be removed and reused with minimum effort and energy usage. The interlocking dry earth blocks is a sustainable solution for 'design for deconstruction' principal which is one of the concepts of circular economy (UK Green Building Council, 2019).

1.1.1. HOUSING AND URBANIZATION IN INDIA

Urbanization in India has become an crucial and permanent process which may not be reversed back. Housing and urbanization is a crucial decisive of national economic development and poverty diminution. Urbanization is the process within which there's a dramatic increase within large number of cities. India is alleged to be within the midst of this huge transition from a predominantly rural to a quasi-urban society. As per the Ministry of Housing and Urban Affairs, "the 2030 development agenda of the United Nations has emphasized the role of sustainable cities by incorporating Sustainable Development Goal (SDG) i.e. Sustainable Cities and Communities for making cities and human settlements inclusive, safe, resilient and sustainable" (MoHUA, 2019).

At current rate of growth, urban population in India is estimated to reach a staggering 575 million by 2030. According to Census 2011, as many as 53 cities in India had a million plus population. As per the projection of MoHUA, more than 50% of the country's population will be urban by the year 2050. According to Census 2011, 377.1 million Indians comprising 31.16% of the country's population, live in urban areas. Urban areas are said to be the "engines of economic growth" and it is estimated that they contribute more than 60% of India's Gross Domestic Product.

The rapid urban growth put pressure on the housing and construction sector to provide housing to meet the growing demands in urban cities. During the year 2019-20, the Ministry interacted closely with UN-Habitat India to push forward the Sustainable Development Goal-11 agenda (MoHUA, 2019).

This high demand for the housing has led to housing scarcity which has set off a need for new innovations, techniques and research that will provide efficient, applicable, easy, quick, less labour intensive and cost-efficient wall construction. One of such technologies that has shown promising results is mortar-less technology development using dry-stack interlocking bricks/blocks (Jhan, P., Beigh, A. M. & Bhowmik, S., 2017).

1.1.2. PROBLEMS IN CONSTRUCTION INDUSTRY

Indian construction industry is moving forward in a fast phase but this rapid growth is causing problems or is affected by problems in the construction and real estate sector. The common problem that occur in construction industry is the lack of labour forces both skilled and unskilled. Majority of construction site in Tamil Nadu depend on migrated labors from other states. This dependency of labour from other states leads to non-availability of labour during festival seasons and other celebration were migrant labors return to their homes. The 2019-2020 Covid-19 pandemic has made this to be true as all the construction works came to a still stop as the labors migrated back to their states. This can be avoided by using local labors. But the local labors either are short in numbers are they cost higher than the migrant labors. All this factors create cost and time issues in a construction project.

As per the report by National Skill Development Corporation, the study on labour based on skill level in the state of Tamil Nadu and the skill gap in the construction is reported as per the table 1.1 (NSDC, 2012).

**Table 1.1 Skilled and Unskilled Human Resource
in Construction Sector in India**

Construction Sector - Human Resource (in 000s)				
Year	Unskilled	Semi-Skilled	Skilled	Total
2012-2017	771	148	73	992
2017-2022	1703	319	154	2176
<i>Source: NSDC, 2012</i>				

From the above table 1.1, it can be understood that the number of skilled labour available in the states is less. This result in decreased quality of work and error in works if the activity is new or foreign. Hence, there is a need for developing new construction techniques where, the need for skilled labour is reduced. Also as there is a shortage of labour in Indian construction industry, which demand for modern technologies which need lesser human resource and labour compared to the conventional building construction methods and technologies.

The interlocking dry earth block technology has huge potential to address this issues as it needs less labor with little skills to complete the activity. The interlocking blocks are self aligning and hence the labor can easily stack them quickly with less attention to details. The interlocking blocks also does not require plastering, curing and other additional process, so the number of labour required is also reduced.

1.1.3. CONSTRUCTION AND DEMOLITION WASTE

As India is moving rapidly towards urbanization, the Indian construction sector is to be come the third largest construction sector in the world. Out of all the building that are to exist in the year 2030, 70% of those buildings are yet to be build. This massive demand for construction need lot of raw materials and resources such as sand, soil, stone, water, etc. But, these resources already face supply shortage as they are finite resources. Hence, conservation of resources is very important. The efficient way to conserve the resources is through reusing and recycling of construction and demolition waste. This waste is currently being dumped in landfills, but this has to be extracted before it reaches the landfill and be used as substitute to raw building materials.

Table 1.2 Construction & Demolition Waste in India

C&D waste generation in select Indian cities		
City	Population (Census 2011)	Daily CDW Generation (tonnes/day)
Mumbai	12,442, 373	2,500
Delhi	16,787, 941	4,600
Bengaluru	8,443, 675	875
Chennai	6,500,000	2,500
Kolkata	4,496, 694	1,600
Jaipur	3,471, 847	200
Patna	2,514, 590	250
Ahmedabad	6,063, 047	700
Bhopal	1,917,051	50
Coimbatore	2,618,940	92
Source: TIFAC, 2001; MoHUA, 2018		

The management of CDW is still a challenge in India. The demolition methods in India is not yet managed and monitored efficiently. The majority of demolition activity is carried out by demolition contractor who take extract materials which are profitable such as steel and wood and other waste such as concrete and brick debris are used as back filling materials or they are dumped in landfills. Only very small percentage of the debris are reused by crushing into smaller sized based on its end use. So, to reduce the CDW, the process of demolition itself shall be researched and the concept of deconstruction shall be adopted. The building which is designed for deconstruction can effectively reduce the generation of wastage as the elements of the structure are designed for step by step deconstruction.

The materials and new technologies that are suitable for deconstruction are researched and experimented in many countries. The design for deconstruction should be done from the preliminary stage / design stage of the project. One of the technology that can support design for deconstruction is interlocking earth blocks which are easy and quick to assemble and the walls can be made in a short time with less resource. The walls can later be removed without damages and reused at another location based on requirement. These interlocking blocks can be resold in the secondary markets so that the life cycle of the blocks are extended and the reuse of materials and secondary market for the construction materials is encouraged. Thus, waste created during construction and demolition is reduced by adopting to interlocking blocks.

1.1.4. SUSTAINABLE DEVELOPMENT

The United Nations Development Programme has developed 17 sustainable goals signed by all UN members in the year 2015 which includes reduce ecological footprint by changing the produce and consume process of resources, efficient management of disposal of waste, encourage reuse, recycle among people and industries, reduce green house gas emission, invest in low carbon development, affordable housing options, etc (UNDP, 2015). India is moving towards sustainable development with adapting to green principles and green rating systems. The rating systems such as Indian Green Building Council (IGBC), GRIHA, LEEDS are rapidly being recognized and adopted.

The green rating systems focus on water conservation, energy efficiency, material and resource conservation, improving indoor environment quality and other factors. The building system and material adopted for a project shall be suitable under all these categories. The interlocking block technology can help in gaining points under several categories under the green rating systems as the technology use very little water, can be reused and recycled. The interlocking blocks are sustainable and eco-friendly as the raw materials can be taken from local region. The raw material can also be replaced by recycled or waste materials such as fly ash. These blocks can also be easily removed and reused after the project life-cycle time is over. The interlocking block is not harmful for the natural environment and the human resource required is also less. The project cost, materials required (as no mortar is required), project time, skill required, maintenance required are all reduced considerably. The points that can be achieved by using dry stack interlocking blocks under various green rating system is studied in this thesis.

1.1.5. POVERTY

India is the second most populated country in the world, just behind China. Many major cities in India is over-populated and the cities are overflowing with people due to migration and urbanization. The cities are unable to keep up with the growing demands due to over-population and the infrastructures and housing needed for the dwellers is lacking behind. Significant portion of the people in India live below poverty line and they can not afford even basic shelter requirements. Due to over-population, poverty and high demand for land area, the property value is also increasing rapidly, making it impossible for the economically weaker section to afford housing. These conditions led to development of slums which make a stain on the aesthetic of the cities. The cities like Delhi and Mumbai are covered in slums which has to be eradicated by providing economical and affordable housing options for the needed.

To provide optimal affordable housing solutions, we must move away from the conventional building technologies and experiment with new and sustainable building materials. The housing solution should also cater to the changing needs of the users as their economical status and family grows, their housing can also grow and adapt.

1.1.6. AFFORDABLE HOUSING SOLUTIONS

Affordable housing solutions are building technologies/systems which are low cost in nature. The affordable housing is needed for the upper LIG, EWS and MIG groups who can not afford to pay for the construction for a house or avail home financing options. The lack of available housing options, combined with limited income and minimal access to home finance for low income borrowers, means that millions of Indian households currently live in cramped, poorly constructed houses/slum areas/shanties. Also, housing constructed by a financially limited person is usually done in stages as per the fund available with the person at a particular time and the house can be added with new floor area after 3 or 4 years as the family grows and the person's finance increase.

The general affordable housing solutions shall have the following characters:

- Increase of construction productivity
- Reduction in construction duration
- Reduced labor cost
- Reduced construction cost
- Technological simplicity
- Local resource dependence
- Easy repair and maintenance
- Quality construction

Mortar-less block construction is a suitable solution for low cost and sustainable construction. It uses less resources (less water, less material, no plaster, no mortar, less labour) and it satisfies all criteria of affordable housing. The mortar-less block construction is more appropriate to many local communities than conventional mortared-brick techniques as it uses locally available raw materials and technologies (Wani, M. V. & Kumar, C., 2018).

There are several low cost housing solutions practised in India and more new methods are being researched and experimented everyday. The commonly available low cost housing technologies are pre-cast construction, pre-fabricated construction, bamboo, concrete blocks, compressed earth block, mud bricks reinforced by natural fibers, fly ash hollow

blocks, AAC blocks, ferro cement, etc (Shinde, S. S., & Karankal, A. B., 2013). Affordability and availability of the materials are the basic requirements of low cost housing but factors such as cultural background and need of the community are also to be considered (Wani, M. V. & Kumar, C., 2018). The interlocking dry earth blocks use traditional mud as raw materials and is allowed to dry in sun naturally instead of burning and baking as done for bricks. Hence, the interlocking dry earth blocks are more traditional and green compared to other materials such as bricks, ACC, concrete block, fly ash block, etc.

1.1.7. CONVENTIONAL BUILDING SYSTEM

In India, brick masonry is one of the most commonly used building materials in all types of construction. The primarily used building material in India is produced from naturally occurring materials such as clay, mud, stones and forest products. These materials are used to produce various building materials such as bricks, blocks, tiles, slabs, etc through different manufacturing processes and chemicals used in them (Deb, A., 1994).

The census conducted by the Ministry of Urban Affairs in 2011 gives details about the type of wall materials prominently used in households in both normal and slum households as given in table 1.3 and 1.4 below.

Table 1.3 Material of Wall in Slum Households in India

Slum households by predominant materials of wall of census houses occupied by them			
Sl. No	Wall Material	No. of Households	Percentage
1.	Grass/thatch/bamboo etc	496,506	4%
2.	Plastic/Polythene	84,952	1%
3.	Mud/unburnt brick	1,878,888	14%
4.	Wood	108,900	1%
5.	Stone not packed with mortar	419,900	3%
6.	Stone packed with mortar	1,535,567	11%
7.	G.I./metal/asbestos sheets	217,487	1%
8.	Burnt brick	8,149,476	59%
9.	Concrete	787,620	6%
10.	Any other	70,128	0%
<i>Source: 2011 Census of India, Ministry of Home Affairs, Gov. of India</i>			

Table 1.4 Material of Wall in Households in India

Households by predominant materials of wall of census houses occupied by them			
Sl. No	Wall Material	No. of Households	Percentage
1.	Grass/thatch/bamboo etc	22,110,488	9%
2.	Plastic/Polythene	822,580	0%
3.	Mud/unburnt brick	58,456,576	24%
4.	Wood	1,694,683	1%
5.	Stone not packed with mortar	8,274,782	3%
6.	Stone packed with mortar	26,544,419	11%
7.	G.I./metal/asbestos sheets	1,439,286	1%
8.	Burnt brick	117,268,740	47%
9.	Concrete	8,615,514	3%
10.	Any other	1,513,160	1%

Source: 2011 Census of India, Ministry of Home Affairs, Government of India

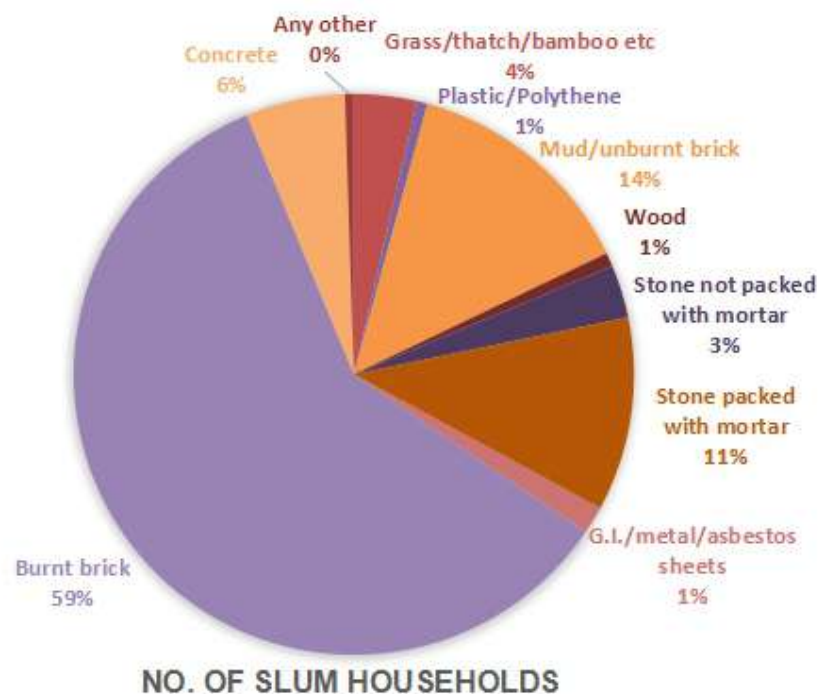


Fig 1.1 Material of Wall in Slum Households in India

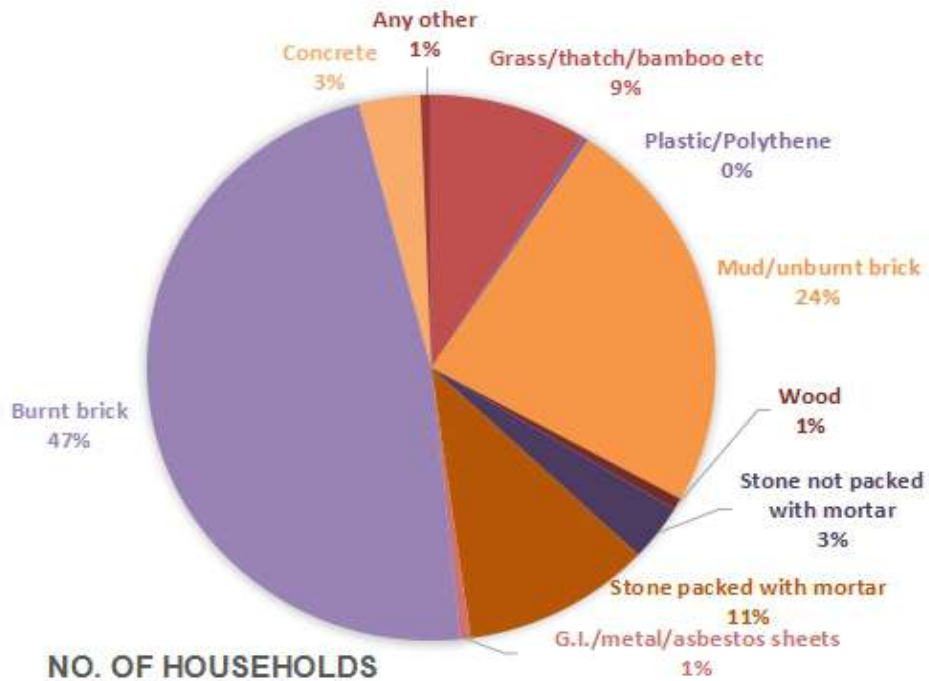


Fig 1.2 Material of Wall in Households in India

From the table 1.3 and 1.4, it can be understood that the most used building material for wall in both general and slum households is burnt brick with 47% and 59% respectively. The second most used wall material is mud/unburnt brick with stone packed with motor as third most common material used in households.

In rural areas, the contemporary building material have made no major impact and brick and mud is still the most used building materials. Whereas in urban areas, the materials such as brick, wood, steel, glass, metals and cement are widely used in construction sectors (Deb, A., 1994). The main reason for a building material to be most prominently used is the labour components. Generally in a construction, the material and labour component shall be in a ratio of 20:80 or 80:20 or within the range depending on the type of project. Brick and similar block material are commonly preferred for construction as they are most familiar for the labour force to use and needs less cost to be spent for skilled labour.

The more innovative and new the technology is, the more skilled the labour is needed. Hence, the cost for labour will increase if the new technology is very varied from the conventional materials. The new materials that are to be developed must be familiar to the labour in its production, composition and usage. The interlocking blocks are very labour friendly as they do not need skilled labour as the blocks are self-aligning and interlocking.

This can reduce the labour cost which can help in cost-less construction. The basic composition of the interlocking earth block is similar to mud blocks which are also familiar to the labour in India.

1.1.8. WATER SHORTAGE IN CHENNAI

1.1.8.1. Chennai Water Crisis - 2019

The 2019 Chennai water crisis was a water crisis occurring in India, most notably in the city of Chennai in Tamil Nadu. On 19 June 2019, Chennai city officials declared that "Day Zero", or the day when almost no water is left, had been reached, as all the four main reservoirs supplying water to the city had run dry. Two years of deficient monsoon rainfall, particularly in late 2017 and throughout much of 2018 had led to this crisis.

Printed from
THE TIMES OF INDIA

Water crunch puts construction down in Chennai

TNN | May 21, 2019, 07:39 AM IST



CHENNAI: Acute water shortage has hit the city's real estate sector and this is likely to delay housing projects. The development comes at a time when the realty market in Chennai was reviving after a slump of more than five years. While developers are raising concerns over depleting water sources, private water tankers, prime source for the construction sector, have cut down supply amid spiralling demand from residents.

Water supply for construction on the water-deficit OMR has dropped by 50%. City-based developer C Chandran, who is executing a housing project of 100 units at Thoraipakkam, said the project has progressed 45% but water crisis has come as a stumbling block.

"We have slowed down construction. We are at a crucial stage and require about 50,000 litres of water a day, but only 24,000 litres is available," Chandran said. Accessing quality water has become a herculean task. "We have pushed the completion to May next year, an extension of four months due to water scarcity," he said.

Article - 1, The Times of India, May 21,2019

The above mentioned article was published in the newspaper - The Times of India, where it states the effect of lack of availability of portable water in Chennai city in summer and this problem continues all summer. This article was one of the motivation for choosing to do research on mortar-less construction technology and interlocking dry earth block technology.

1.1.8.2. Impact on Construction Sector

As the Chennai Metrowater Supply and Sewerage Board (CMWSSB) was forced to reduce piped water supply, construction and real estate industry in which water is important and one of the key elements in the construction process and is required from the initial build-up to the final completion of project. RE developers and construction companies had to buy water from private players in dire situations for very high charges which had a huge impact on the business. Developers who can not afford to purchase water had to put the project in stand-still for a long period of time.

Water usage in building construction industry has to be reduced as the availability of portable water is very limited in cities like Chennai, Bangalore. The Construction and building materials are depended on water which leads to problems in completing the project due to shortage of water available. Hence, this dependency in the water has to be reduced for project to not be affected by water shortage and also pave way for sustainable construction and water conservation.

Mortar-less construction is one of the best methods to reduce the usage of water in construction projects. The need for mortar, plaster and curing is reduced completely and the water needed for these activities is conserved.

1.1.9. MORTAR-LESS WALL CONSTRUCTION

Mortar-less (Dry stacking interlocking block) wall construction is very advantageous masonry construction methods compared to conventional block construction with mortar wall construction. The mortar-less construction eliminates the need for the mortar layer in between bricks/blocks. The mortar-less wall are blocks that are interconnected through interlocking protrusions and grooves. These grooves and patterns help in dry stacking the blocks without the need for mortar. “The goal in any interlocking system is to ensure efficient construction formation with well-aligned masonry structures, even without skilled masons” (Jaafar, M. S., Alwathaf, A. H., Thanoon, W. A., Noorzaei, J., & Abdulkadir, M. R., 2006).

Mortar-less wall construction can be used to both load bearing and non load bearing wall structures. Mortar-less technology make wall construction quick and easy build without skills and expertise of professional block layers. Mortar-less construction offers savings in construction time and labour cost and reduce wastage associated with mixing mortar on site. This technology creates very little mess on construction site such as sand, cement bags,

mortar droppings, etc and the blocks can be laid wet or dry, even be laid in the rain conditions.

1.1.9.1. Load bearing wall - mortar-less construction

The mortar-less wall with load bearing characters can be constructed by core filling grout. These grout filled finished walls are equivalent to the reinforced concrete walls and have superior strength when compared to the mortar block construction. A load bearing wall has to resist both axial and transverse loads which are borne by both horizontal and vertical reinforcement steel rods which are provided in mortar-less wall construction. The core filled with grout provide adequate cover for the reinforcement rods which add strength to the walls.

The interlocking blocks are designed with hollow zones to provide adequate cover for the reinforcements as the rods has to be protected against corrosion caused by elements. The reinforced interlocking block wall construction is not very common in India. Indian mortar-less construction uses reinforced interlocking blocks for columns and other wall portion are dry stacked with interlocking blocks. However, for earth quack resistance buildings, the reinforcement rod can be placed both horizontally and vertically withing the cavity of the blocks at distance as per the engineer's requirements. The interlocking blocks manufactured in countries like Australia, Sri Lanka, Canada has already groves and provisions for both horizontal and vertical reinforcement placement.

The variety of interlocking blocks such as Haener block, Mecano block, Putra block, Azar block, Auram block, Hydraform block are all suitable for load bearing wall construction. They can be reinforced with grout filling to make it load bearing.

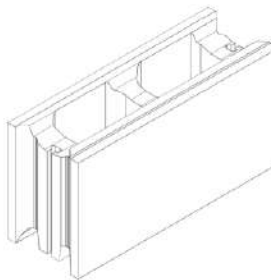


Fig 1.3 Smart Masonry™ Building System - Stretcher Block

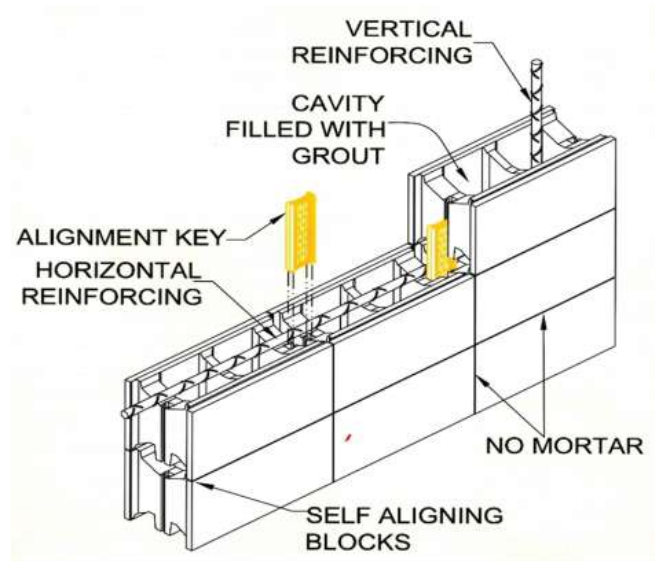


Fig 1.4 Smart Masonry™ Building System - Block with Reinforcement

Fig 1.3 and 1.4 shows an example of interlocking block design in there there is a provision for horizontal and vertical reinforcements. As per the Smart Masonry Building System which is an awarded Australian technology, the interlocking block are smarter, more cost effective method of wall construction while eliminating the use of mortar by using a dry stacked, steel reinforced and core filled system (The Smart Masonry™ Building System, 2017).

1.1.9.2. Non-load bearing wall - mortar-less construction

The interlocking blocks are normally load bearing as it is the efficient form of construction at a affordable cost. The blocks can also be used as non-load bearing partition walls with just dry stacking the blocks with no reinforcement or grouts. These non-load bearing blocks are flexible and can be removed and reassembled easily as per the user requirement and room requirements. The hollow interlocking blocks without grout filling can be used for non-load bearing wall construction.

1.1.10. CIRCULAR ECONOMY - DESIGN FOR DECONSTRUCTION

Natural materials play a very important role in the building industry and construction sector is extremely dependent on them. Without iron there would be no steel; without trees, no timber; without aggregate, no concrete, which means there wont be any structural members without natural raw materials. “If the human race is to minimise its extraction of natural resources then the solutions seem to be to either stop using natural materials (which would appear to be impossible) or to reuse the materials that have already been extracted. This

ideology is known as closing the material loop” (Tingley, D. D., 2013). Reducing the wastage of construction material and demolition waste is the first step to be taken by the industry in closing the loop. The amount of wastage being sent to landfill has to be curtailed. This calls for circular economy principles in construction industry.

“A circular economy is an industrial system that is restorative or regenerative by intention and design. It replaces the ‘end-of-life’ concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models” (MacArthur, E., 2013).

The circular economy is defined as:

“A circular economy is one that is restorative and regenerative by design, and which aims to keep products, components and materials at their highest utility and value at all times, distinguishing between technical and biological cycles” - Ellen MacArthur Foundation.

As per the Ellen MacArthur Foundation, the aim of the circular economy are,

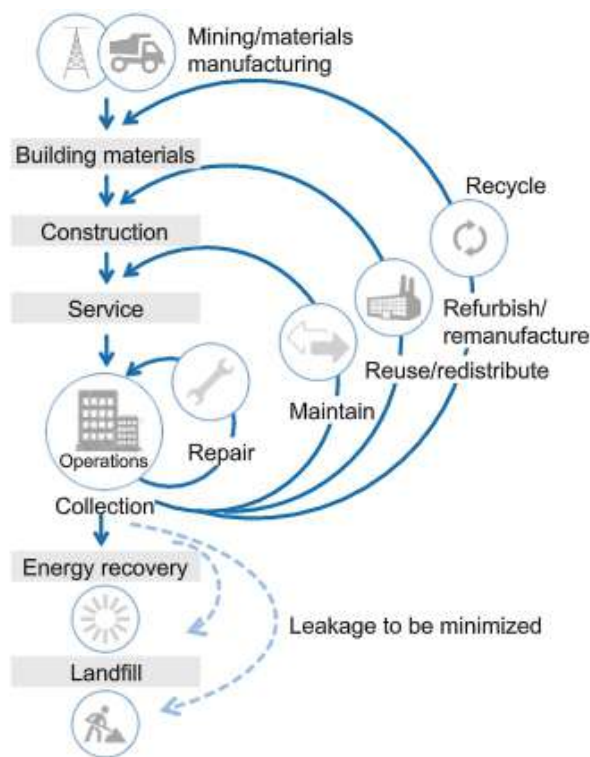
- Design out waste to conserve and limit use of resources.
- Products are designed and optimised for a cycle of disassembly and reuse.
- Product are designed from start for reuse, durability.
- Unlike in today’s ‘buy-and-consume’ economy, durable products are leased, rented, or shared wherever possible.
- Minimise the material usage to develop the product.
- diversifying reuse across the value chain, as second-hand material market must gain traction.
- increase collection and redistribution efficiency while maintaining quality, particularly of technical materials, which, in turn, extends product longevity and thus increases material productivity.

As per the UK Green Building Council, The major principles of circular economy are us under:

- | | |
|-----------------------------------|---|
| 1. Reuse Existing Assets - | Recover materials and products on site or from another site, Share materials or products for onward reuse |
| 2. Space Optimization - | Longevity, Flexibility, Adaptability, Assembly, disassembly, and recoverability, Build space optimization |

- | | |
|----------------------------------|---|
| 3. Standardization - | Industrialization, Modular Construction, Pre-cast Structure, Pre-Fabricated Structure |
| 4. Product as a Service - | Selling products by manufactures as service instead of product. user/client shall not have ownership of the product. |
| 5. Construction Impact - | Use low impact new materials, Use recycled content or secondary materials, Design out waste,Reduce construction impacts |

In construction, Circular Economy is about reducing the demand for non-renewable virgin materials, reducing the production of waste, and maximizing the value of recovered materials used throughout all stages of the programme; construction, maintenance and end of life. To have maximum impact, the circular economy needs to be considered throughout design, specification, procurement, and construction of the programme.



Source: Ellen MacArthur Foundation; World Economic Forum; The Boston Consulting Group

Fig 1.5 Closing the loop - Circular Economy

The methods of implementing circular economy principles shall start from salvaging and reuse of construction and demolition waste (CDW) and creating new building materials from them. The initial step of implementing circular economy principles in Indian construction sector shall be to discover new materials, new building design, new construction methods, new waste management methods and new legislation. By using existing CDWs, the raw material usage is reduced/replaced with reclaimed waste thereby reducing pressure on finite resources.

The Indian residential construction industry is undergoing drastic changes where people are moving from individual housing to apartment housing due to rapid urbanisation that is taking place in urban cities. This has resulted in increased demand for apartment buildings and due to shortage of lands, the existing individual housings are being demolished and converted into grouped housing. This changes may be carried out effectively if the principles of circular economy are involved.

The first step shall be discovering building elements/materials that shall be made from recycled CWD. These materials shall also be designed such that they can be reused again in a new project without involving any massive processes. The material shall be such that it can be constructed and de-constructed easily. This involves proper designing of material and creative construction methodology where care is taken for de-construction of the building. For example, the block work can be made from interlocking bricks instead of normal bricks which require plastering which make the bricks hard to be reclaimed with its potential fully intact.

The new construction model shall be designed such that the building shall be designed for deconstruction. New materials and technologies shall be implemented. The waste generation at site shall be made zero. The usage of resources such as manpower, water, etc shall also be managed effectively. This model shall have least effect on the environment and the consumer shall be satisfied as per their needs and requirements.

The selection of construction material is important part of the design for deconstruction . It should be considered from the pre-design stage. A building that is designed for efficient deconstruction and reuse/re-distribution can reduce many negative effects of the conventional building and become sustainable in nature. The deconstruction design shall not only help in the end of building life, but it can also be helpful for retro fitting of building and increase the flexibility and adaptability of the building.

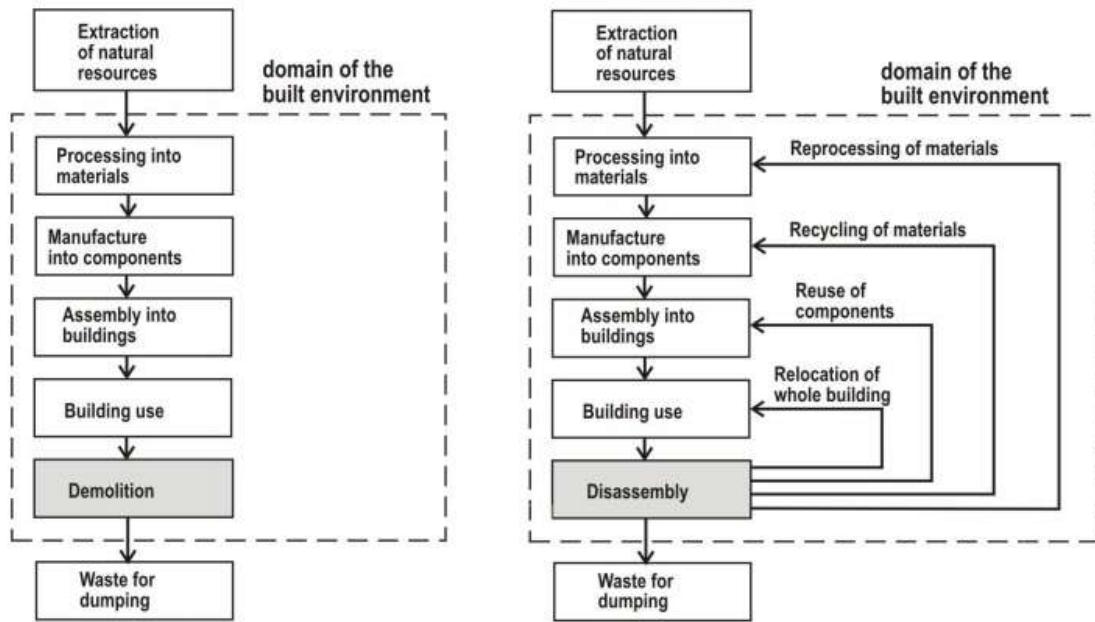


Fig 1.6 Conventional Demolition vs Disassembly
(Crowther, P., 2002)

From fig. 1.6, it can be understood that the waste from construction industry can be reduced by disassembly instead of demolition of structures. Large amount of CDW is generated as the buildings are simply demolished instead of being disassembled. The building material's life cycle can be extended by reusing and recycling and re-distribution of the building components. The interlocking dry stack blocks are suitable for disassembly as the wall masonry with interlocking blocks can be erected easily and quickly but also be disassembled and reused readily in the same project or for other projects.

1.2 NEED FOR RESEARCH

The Construction Industry is responsible for over 30% of the extraction of natural resources, as well as 25% of solid waste generated in the world. India is expected to become third largest construction market in the world. In India, construction is the second largest economic activity after agriculture. Hence, As Construction industry plays a key role in the economy of India, it can have huge impact in the economy and environment. As construction industry adopts liner economic model (take, make, dispose), the amount of debris and construction waste generated is huge. This leads to the materials not being used to its full potential.

Adoption of a Circular Economy model shall aim at keeping the materials in a closed loop to retain their maximum value, therefore with a greater potential of reducing the waste generation and resources extraction for the Construction Industry. Designing the material to be reused in its original stage without going into recycling process can benefit the economy and environment.

The interlocking block construction shall have huge benefits to urban cities like Chennai which faces heavy water crisis for the past few years. Changing to this construction technique which uses very less water as water required for plastering, mortar, concreting, curing, etc are all eliminated shall benefit for the real estate and construction sector of the city.

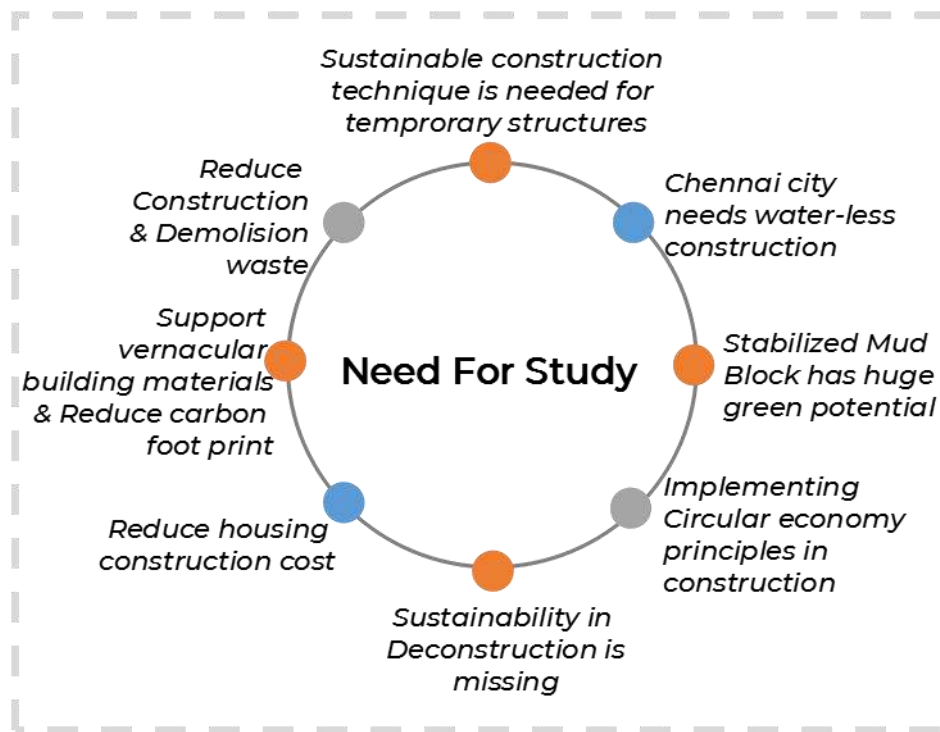


Fig 1.7 Need for Study

1.3 AIM AND OBJECTIVE OF THE RESEARCH

1.3.1. Aim

The aim of this project is to implement the circular economy concept of design for deconstruction by using interlocking dry mortar-less earth blocks which is a sustainable tool and construction technology with varied benefits and advantages.

The project shall aim to create guideline and quality checklists for interlocking block construction to cater to the design for deconstruction principal and analysis its sustainability attributes such as energy efficiency, water conservation, material & resource conservation, earth-quack resistance construction technique, fast construction, cost efficient constructions, etc.

1.3.2. Objective

The objectives of this thesis shall be,

- ◆ Analysis the potentials of Interlocking dry earth block construction.
 - Water efficiency
 - Cost efficiency
 - Time efficiency
 - Energy efficiency
 - Reducing carbon foot print
 - Reuse & Recycle potential
 - Earth-quack resistance
 - Thermal comfort
 - Material & Resource efficiency
 - Labour efficiency
- ◆ Analysis the existing construction techniques and methods of interlocking dry earth block masonry construction.
- ◆ Frame new construction techniques and methods to suit for the design for deconstruction principal.
- ◆ Frame guideline and procedure for construction and deconstruction of IDEB construction.
- ◆ Frame checklists for quality construction and deconstruction of IDEB construction.

1.4 RESEARCH METHODOLOGY

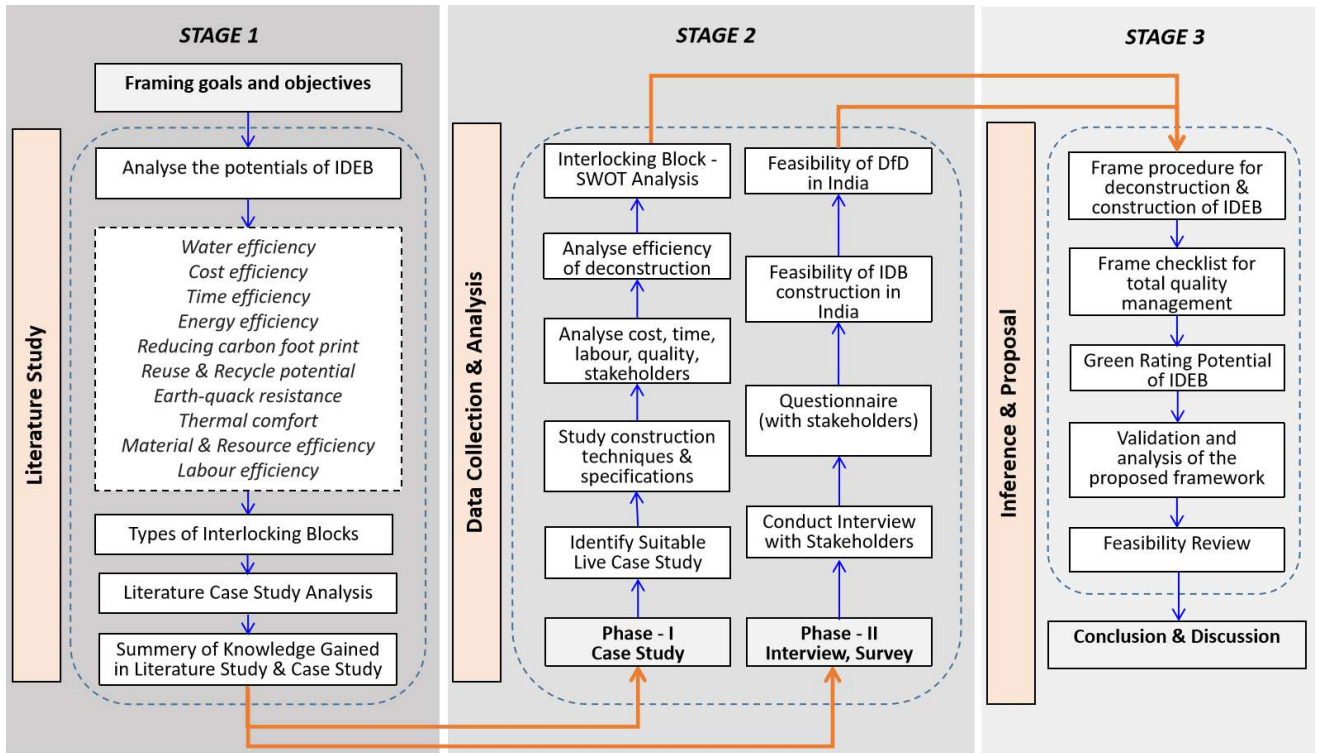


Fig 1.8 Research Methodology

CHAPTER 2

LITERATURE REVIEW

2.1. MORTAR-LESS CONSTRUCTION

2.1.1 History of Interlocking Blocks

The history civil engineering started with the evolution of masonry construction. The ancient civilization used naturally available stones as building material which makes masonry the oldest building material known to humans. The random rubble dry masonry is the first form of construction using stones (Narendra, T. 2010).

The brick manufacturing methods of the ancient civilization was replaced by the modern brick manufacturing system which as been developed and improved upon for the past two decades. The shortcomings of the ancient brick making methods were resolved and the bricks were made quicker and in better quality and finish using the brick molds and machines and the bricks are both sun dried and/or burnt in kiln. However, due to modern technological advancements and current trends, the bricks are developed in different classifications such as solid bricks, hollow bricks and interlocking bricks. The development of interlocking blocks has led to unlocking the potential of fast and cost efficient construction (Al-Fakih, A., Mohammed, B. S., Nuruddin, F., & Nikbakht, E. 2018, April).

2.1.2. INTERLOCKING BLOCKS FOR CONSTRUCTION

After the development of interlocking bricks, its presence has had a huge impact in the construction industry across may countries. As it is more profitable and efficient with sustainable properties, it has been taken up by construction industry across countries as it also reduces the prerequisites for very particular works. The interlocking block masonry has adopted as a replacement of conventional brick masonry for its multiple convenience and benefits as it can also replace concrete walls to an extent. The interlocking blocks are now available in different types based on raw materials used and interlocking designs. The utilization of interlocking block has gained popularity across several countries as it is a profitable and sustainable building material.

The interlocking blocks are different from the conventional bricks as they do not require mortar and can be dry stacked to construct walls. This makes the building of walls and partitions easier, cost efficient, less messy, quicker and less labour required (Al-Fakih, A., Mohammed, B. S., Nuruddin, F., & Nikbakht, E. 2018, April). The interlocking blocks still

faces the similar problems faced by the bricks such as low strength, higher water absorption, low fire resistance and high porosity (Irwan, J. M., Zamer, M. M., & Othman, N. 2016). These shortcomings were slowly overcome as there is a need for the improvements in the interlocking block technology as they have to compete with other building technologies such as concrete works, steel works and brick masonry. The last decade in the construction industry has seen several rapid changes in the construction technologies and construction materials as the industry is moving towards adopting more sustainable approaches. At the same time, the industry is also in need of quick and less labour intensive works which can be carried out at lower costs. This changes has led to the construction industry moving towards pre-cast and pre-fab construction technologies. To cater to this growing industry demands and as a solution to address the problems in interlocking blocks, several improvements such as differing composition of raw materials, stabilized mud blocks, fiber reinforced blocks, surface bond masonry, grouted masonry and dry block masonry were developed.

The primary function of Masonry is carrying load and enclosing space, while possessing strong properties for fire resistance, thermal and sound insulation and protection against environmental exposure. Conventional masonry construction, especially for smaller units, leads to a large number of mortar joints (Korany, Y., & Humphrey, S. 2010). This can be solved by using interlocking blocks which reduce these joints during construction and the wall can be erected without height limitation at a single day in case of dry stacking of interlocking blocks. Several interlocking block types are available based on type of interlocking mechanism, materials, hollow/solid, reinforcement types, etc. They are studied further in the study.

2.1.3. TYPES OF INTERLOCKING BLOCKS

Different types of interlocking blocks have been developed over the years based on varying composition of materials, sizes and dimensions, shapes, strengths, interlocking patterns and usages (Al-Fakih, A., Mohammed, B. S., Nuruddin, F., & Nikbakht, E. 2018, April). The interlocking block shall be two way interlocking (horizontal and vertical) and one way (vertical) interlocking only (Anand, K. B., & Ramamurthy, K. 2005). Although there are various types of interlocking blocks available in the literature and research papers, there are only limited types of interlocking blocks available with detailed structure and stability analysis. The test results and lab reports on the behavior of the interlocking blocks are recorded for certain types and models only.

As per the study made by K. B. Anand and K. Ramamurthy, the different types available are Solid or nearly solid systems, the TASTA system, the Sparfill system, and the SILBLOCK

system have the limitation that they cannot be adapted to seismic applications. Some of the systems that enable reinforcing and have been recommended for adoption in earthquake resistant construction are Mecano system, the Haener system, the Modified H-block system, the WHD block system, Azar block, Faswall system and the IMSI system (Anand, K. B., & Ramamurthy, K. 2005).

There has been a initiative across countries to develop innovative and efficient interlocking blocks in recent years. The various types of interlocking blocks across various countries are listed in the table 2.1 below.

Table 2.1 Types of Interlocking Block Models (Based on available literature)

S. no	Interlocking Block Model	Country	Year	Material	Structure System	Reinforcement	Density
1.	Haener block system by Juan Haener	Canada	1994	Concrete	Load bearing	Horizontal & Vertical	Hollow
2.	Mecano block system	Peru	1988	Sand, lime	Load bearing	Horizontal & Vertical	Hollow
3.	modified H-block & W-block by Drexel University	USA	1992	Concrete	Load bearing	Horizontal & Vertical	Hollow
4.	Solid Interlocking Block (or Sillblock) system by Indian Institute of Technology, Madras	India	2000	Concrete	Load bearing	horizontal only (in corner only)	Solid
5.	Putra Block by Housing Research Centre (HRC) of University Putra Malaysia (UPM)	Malaysia	2004	Concrete	Load Bearing	vertical only	Hollow
6.	HILBLOCK (Hollow Inter -Locking Block) by Indian Institute of Technology, Madras	India		Concrete	Load Bearing	Vertical and Horizontal	Hollow
7.	Thai interlocking brick by Human Settlement Division of the Asian Institute of Technology (HSD-AIT), & Thai Institute of Scientific and Technical Research(TISTR)	Bangkok	1980	Sand, Clay, lime	Load bearing	Vertical	Semi - hollow

8.	SOLBRIC system	South Africa		Sand, Clay, lime	Load bearing	Horizontal	Solid
9.	Hydraform system	South Africa		Sand, Clay, lime	Load bearing	Not Applicable	Solid
10.	Bamba interlocking brick	South Africa		Sand, Clay, lime	Load bearing	Horizontal and Vertical	Semi-hollow
11.	Auram Interlocking Brick	India		Sand, Clay, lime	Load bearing	Vertical	Semi-hollow
12.	Tanzanian Interlock Brick (TIB) system	Africa		Sand, Clay, lime	Load bearing		
13.	U.S. Pat. No. 6,105,330 of Nanayakkara	US		Concrete	Load bearing	Vertical and Horizontal	Semi-hollow
14.	Verot Oaks Building Blocks, Inc. (VOBB)			Concrete	Load bearing	Horizontal	Hollow
15.	Interlocking Stabilised Soil Blocks (ISSB)	Africa		Sand, clay, lime	Load bearing	Non Applicable	Solid
16.	The Smart™ Masonry System	Australia		Concrete	Load bearing	Vertical and Horizontal	Hollow
17.	Azar Dry-Stack Block system	Canada		Concrete	Load bearing	Vertical and Horizontal	Hollow
18.	Connex™ Mortarless Block System by Boral	Australia		Concrete	Load bearing	Vertical and Horizontal	Hollow
19.	FlexLock system by Cercorp Initiatives	US		Concrete	Load bearing	Not applicable (Post tension tendons)	Hollow
20.	Spar-Lock System	US		Concrete	Load bearing	Vertical and Horizontal	Hollow

The interlocking blocks are also available in different types based on the raw materials used. The various materials compositions available are, Interlocking Bricks Utilizing Wasted Polyethylene Terephthalate (PET) (Alaloul et al. 2020); GFRP with maximum percentage of fly ash in interlocking brick (Watile, R. K., Deshmukh, S. K., & Muley, H. C. 2014); interlocking cement block with fly ash and bamboo, GFRP, steel rod as reinforcements (Lateef, A. B. A., Ashmi, S. M., Mannan, M. F. A., Ali, M. A., Hussaini, S. A., 2018), Sand and lime mix, cement and sand mix, etc.

As per the author Bansal Deepak, in his research paper, he has stated that the interlocking block masonry system is not uniform in India, and as per information available there are three types of interlocking blocks available in India (Deepak, B. 2012):

1. Hydraform Interlocking Blocks (stabilized earth blocks(SEB) and fly ash blocks)
2. IIT Delhi, India, fly ash interlocking blocks
3. IIT Madras, India, cement concrete interlocking blocks

2.1.3.1. Haener Blocks

The haener concrete blocks are of size 8" x 8" x 16" and weigh 34 pounds. The half block is of size 8" x 8" x 8". The size are also available in 6", 8" and 12" (Wani, M. V. & Kumar, C. 2018). "Haener Block is a two-block building system that lays up to 10 times faster than conventional block, at a fraction of the project cost of conventional," states Larry Bouchard, Vice President of Business Development for Haener Block. "After a masonry supervisor Starts the first course level and plum, any available workers can then stack as many as 800 blocks a day each, producing perfectly self-alignment walls and corners".

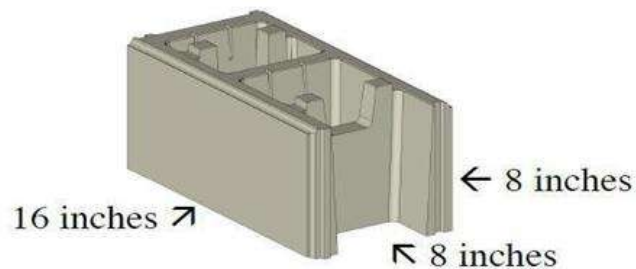


Fig 2.1 Haener Concrete Block
(Wani, M. V. & Kumar, C. 2018)

In 1994, Haener block system was developed in Canada by Juan Haener. The block was made from concrete and it was used for the construction of load bearing walls (Bosro, M. Z. M.,et al, 2018, April). The system comprises of three types of block units as in Fig. 2.2 The block has hollow gaps which allows both horizontal and vertical reinforcement to be embedded in the grout filled in the hollow sections to act as load bearing walls where the reinforcement are placed at intervals as per the engineer's design.

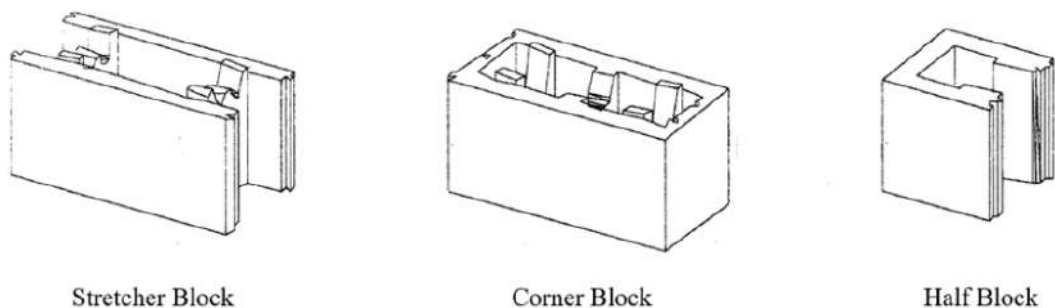
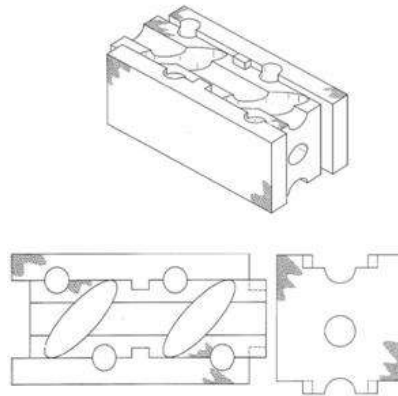


Fig 2.2 Haener Concrete Block Units
(Bosro, M. Z. M.,et al, 2018, April)

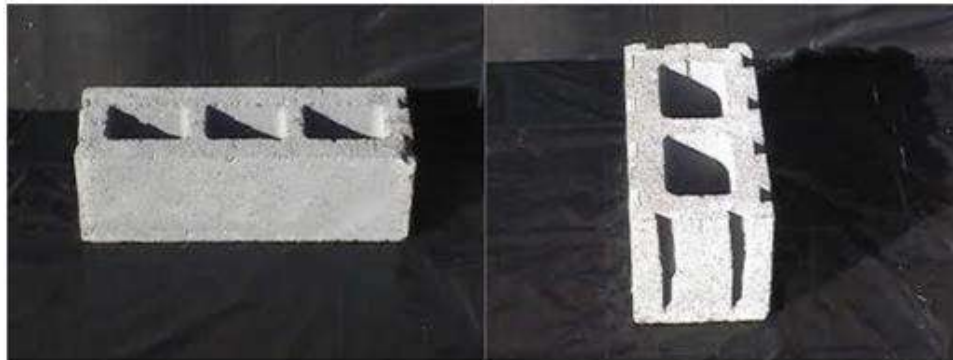
2.1.3.2. U.S. Pat. No. 6,105,330 of Nanayakkara



***Fig 2.3 Concrete Block-U.S. Pat. No. 6,105,330
(Wani, M. V. & Kumar, C. 2018)***

The concrete block can resist lateral loads and is a partially hollow building block with solid rectangular exterior configuration in which one entire end surface of the building block exhibits a positive deep key geometry and the opposing end surface exhibits a negative deep key geometry complement to the positive geometry of the opposite end (Wani, M. V. & Kumar, C. 2018). The deep key interlocks also exhibit between opposing horizontal block surfaces as positioned between vertical cavities as the block narrows in the negative direction. In addition, there is created a substantially rugged and load resilient interlock between vertical and horizontal complementary surfaces when joined as components of a wall structure.

2.1.3.3. Verot Oaks Building Blocks, Inc. (VOBB)



***Fig 2.4 VOBB Concrete Block
(Wani, M. V. & Kumar, C. 2018)***

The dry-stacked units are available in six inches high and six inches wide. The units are also available in sizes 18" (22-31 pounds), 12" (15-21 pounds) and 6" lengths (7-11 pounds). The units use grooves and special removable clips to help keep them aligned until the grout is poured or pumped into the cavities (Wani, M. V. & Kumar, C. 2018).

2.1.3.4. AURAM Blocks



***Fig 2.5 Auram Block
(Wani, M. V. & Kumar, C. 2018)***

The Auram block is hollow interlocking blocks which was developed by the Auroville Earth Institute, which is earthquake resistant, has been approved by the Gujarat State Government. The average wet compressive strength achieved with the local soil stabilized with 8-9 % cement using these presses is around 50 kg/cm² (Wani, M. V. & Kumar, C. 2018)



***Fig 2.6 Auram Hollow Interlocking Block
(Auroville Earth Institute)***

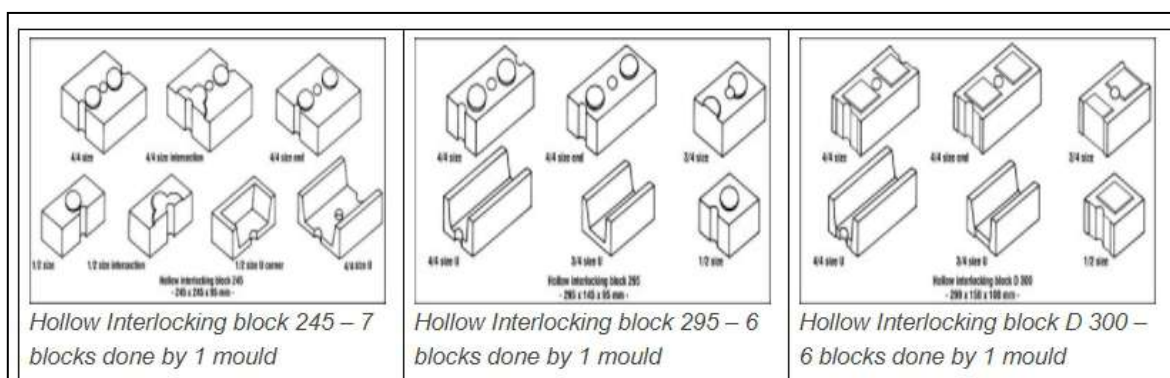


Fig 2.7 Auram Hollow Interlocking Block - Types
(Auroville Earth Institute)

Hollow Interlocking block 245 – 7 blocks done by 1 mould: This block 245 can be used up to two storey buildings. The block is laid with a stabilised earth mortar of 5 mm. A concrete grout is cast later on into the holes. The module of the block (dimension including the mortar thickness) is 25 x 25 x 10 cm.

Hollow Interlocking block 295 – 6 blocks done by 1 mould: This block 295 can be used for single storey buildings only. The block is laid with a stabilised earth mortar of 5 mm. A concrete grout is cast later on into the holes. The module of the block (dimension including the mortar thickness) is 30 x 15 x 10 cm.

Hollow Interlocking block D 300 – 6 blocks done by 1 mould: This block D 300 can be used for single storey buildings only. This block is dry stacked and a concrete grout is cast later into the holes. This grout flows in all the holes as well as the vertical and horizontal joints due to the special profile of the block. The module of the block (dimension including the mortar thickness) is 30 x 15 x 10 cm



Fig 2.8 Auram Press 3000
(Auroville Earth Institute)

The accuracy of the Auram press allows a very regular block height: only 0.5 mm difference in height. This allows the block to get the ideal mortar thickness of 5 mm or to have dry stacked blocks which are then grouted with a concrete. The holes have been maximized (regarding the size of the block and the press design) at 5 cm diameter to allow a proper concrete cover for the steel.

The area of the key has been maximized at 9 cm diameter for the blocks 245 and 295, so as to ensure the maximum adhesiveness of the key on to the block body, so as to resist the shear effect. The height of the key has been determined by having the maximum friction area between blocks to resist the shear and by having the minimum friction on the mould while de-moulding the block from the press. The chamfer angle of the key seeks to be optimum. The keys of the hollow interlocking block Dry 300 are square so as to get an effective interlocking.

The hollow interlocking block technology developed by the Auroville Earth Institute has been approved by three governments

- The government of Gujarat, India, as a suitable construction method, up to two floors high, for the rehabilitation of the zones affected by the severe earthquake of January 2001 in Kutch district.
- The Government of Iran (Housing Research Centre) as a suitable construction method, up to 8 m high (two floors), for the rehabilitation of the zones affected by the 2003 earthquake of Bam.
- The Government of Tamil Nadu, India, (Relief and Rehabilitation) as a suitable construction method for the rehabilitation of the zones affected by the 2004 tsunami of Indonesia.

2.1.3.5. Interlocking Stabilised Soil Blocks (ISSB) - Africa



***Fig 2.9 Interlocking Stabilised Soil Blocks
(Perez, A. 2009)***

As per the report by the UN-HABITAT written by Adrian Perez on studying the Interlocking Stabilised Soil Blocks Appropriate earth technologies in Uganda, the ISSB is made by compacting earth and mixing it with stabilizing supplements. The technology was developed studying already existing technologies such as CINVA-RAM press in the 1950s by the Chilean engineer

Raul Ramirez for the Inter-American Housing Center in Bogota, Colombia (CINVA), Human Settlements Division of the Asian Institute of Technology (HSD-AIT) along with the Thailand Institute of Scientific and Technological Research (TISTR). The Soil stabilization by application of additional supplements or forces to the soil make the blocks more waterproof and stronger.

ISSB technology machine produces blocks with a double interlock. Technical specification of the manual ISSB machine used in East Africa:

- ✓ Typical compression force: 80-100N
- ✓ Weight: 140kg (portable)
- ✓ 2-4 workers in an 8hr work day can produce 400-600 blocks
- ✓ Low maintenance: requires to be lubricated with engine oil.
- ✓ 130 stabilised blocks can be produced from a 50kg bag of cement.

The different types of ISSB are (Perez, A. 2009),

- a) Straight Double Interlocking Block: The most commonly used block for wall creation.
- b) Curved Double Interlocking Block: Used for making water tanks and sanitation facilities.
- c) Wide Format interlocking Block: Allows for stronger, thicker walls, especially useful when making high walls.
- d) Straight Single Interlocking Block: Contains a larger face, hence less blocks are needed to cover wall area. This was the predecessor to the straight double interlocking block.
- e) Grooved Double Interlocking Block: The grooves of this block facilitate plastering, however, this machine is no longer produced.

The various forms of stabilisation components are cement or lime, fibrous, chemicals and resins or sand and gravels. The size of the ISSB is 26.5cm x 14cm x 10cm. The weight of an unit block shall be 8-10kg. These blocks can create smooth and flat surface. The number of blocks required to cover per sqm area is 35 nos. The density of the block is 1700-2200 kg/m³.

2.1.3.6. Interlocking Compressed Soil Blocks (ICSB) - Thailand



TISTR IB, Model 1 (1982)



TISTR IB, Model 2 (1998)



TISTR IB, Model 3 (actual)



TISTR IB, Model 4 (current with link-hole depression for more than 2 story bearing)

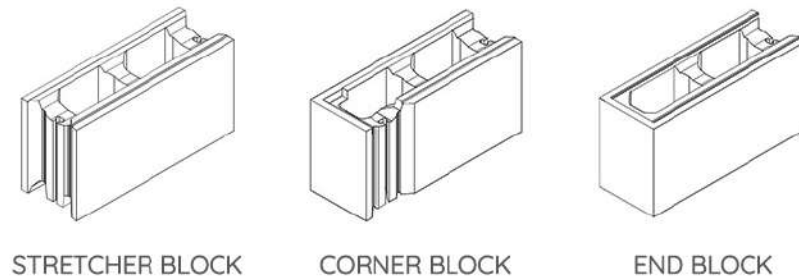
***Fig 2.10 Interlocking Stabilised Soil Blocks by TISTR
(Bredenoord, J. et, al. 2019)***

ISSB are eco-friendly building material for home building and structures such as water tanks and sanitation facilities which is developed for several decades by Thai R&D Institute TISTR. These interlocking construction blocks are made of local raw materials – earth, loam, or soil – which are mixed in the right proportion with a low percentage of cement, and compressed using simple machinery. The resulting building blocks usually have high compressive strength and are suitable for constructing both outer and inner walls with load-bearing capacity (Bredenoord, J. et, al. 2019). The size of the ISSB is 25cm x 10cm x 12.5cm. The compressive strength of the blocks is more than 70Ksc.

2.1.3.7. The Smart™ Masonry System

The smart masonry system was developed, in Australia, as an approach to a faster and efficient building system. The system contains three types of blocks based on its usage and they have provision for vertical and horizontal reinforcements. The hollow areas can be

filled with grout which can make the wall system equivalent to RCC shear wall. The block wall is capable of taking up to 3000psi of load. These blocks are made of concrete blocks and they are strong enough to withstand seismic activity, changing weather conditions, fire, noise, and environmental degradation. There is a special alignment key system for accurate alignment and locking mechanism.



***Fig 2.11 The Smart Masonry System - Stretcher Bond
(Source- The Smart™ Masonry System)***

The size of the block are 40cm x 14cm x 20cm and 40cm x 11cm x 20cm. The weight of the block ranges from 10.5kg to 13.5kg. The cement to sand ratio used majorly is 1:5 and can achieve compressive strength from 550psi to 2500psi.



***Fig 2.12 The Smart Masonry System - Method
(Source- The Smart™ Masonry System)***

2.1.3.8. Connex™ Mortarless Block System

The Boral, an Australian building material manufacturing company has developed an interlocking block system - Connex Mortar-less block system. The system has three blocks

for wall thickness of 20cm, main stretcher block which is 40cm x 20cm x 20cm in size; corner block which is 40cm x 20cm x 20cm; and half block which is of size 20cm x 20cm x 20cm. The weight of the block is 16kg per unit. For 15cm thick wall, main stretcher block is 40cm x 20cm x 15cm in size; corner block which is 35cm x 20cm x 15cm; and half block which is of size 15cm x 20cm x 15cm. The weight of the block is 10.8kg to 16kg per unit.

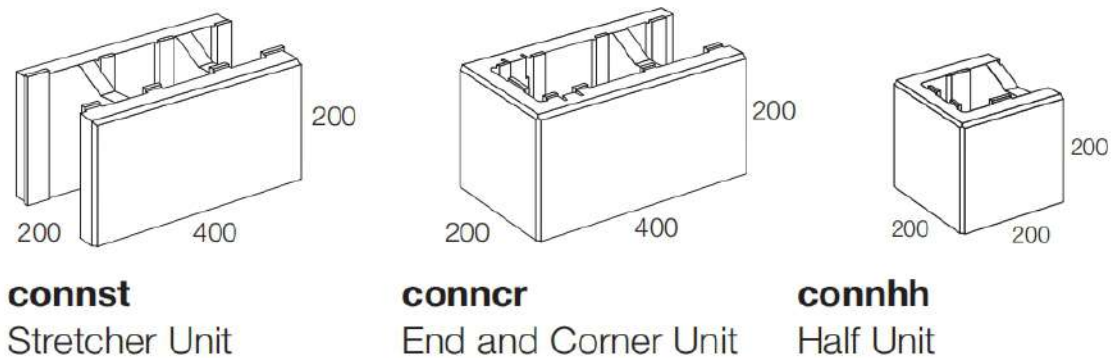


Fig 2.13 The Connex™ Mortarless System - Blocks
(Source- The Connex™ Mortarless System)

The Boral Connex™ Block system is a dry mortarless wall system that when core-filled and reinforced is suitable for load bearing, blade and retaining walls. It can also be used for non-load bearing walls when partially core-filled and reinforced. The System comprises of two ranges of block systems consisting of three modular components that key together, thereby eliminating the need for mortared joints above.

The benefits of using Connex™ system are,

- The system is quick and easy to install.
- It can be laid quicker than hollow blocks.
- First course is fully mortared and the rest of the course is dry stacked.
- It reduced wet waste on site.
- It is a good alternative to Do-It-Yourself (DIY) construction.
- It is a simple modular system as there are only three units available.
- The interlocking blocks of 150mm thickness has fire rating of 3 hours and blocks of thickness 200mm has fire rating of 4 hours.

2.1.3.9. FlexLock system

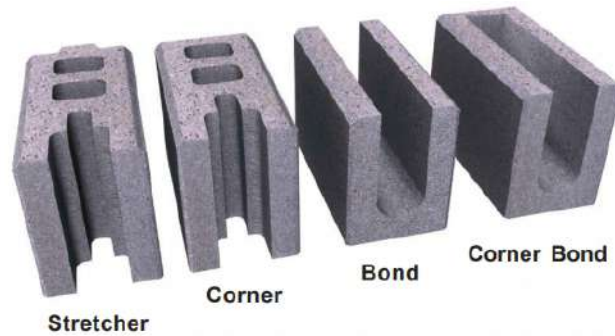


Fig 2.14 The FlexLock System - Blocks
(Source- The FluxLock System - Cercorp Initiatives Inc)

As per Cercorp Initiatives, “The FlexLock® Wall System is a complete masonry system designed as a mortarless alternative to standard concrete block construction. The system’s multi-patented technology produces significant competitive advantages through the use of an interlocking design, precision bearing surfaces, and post-tensioned tendons.” The system is mortar-less with reduced work force and construction time requirements. The system allows the work to be carried out at all seasons. The special feature of this system is that the entire system is completely reusable as the parts can be disassembled readily due to metal bolt nut connection joints. This also makes it easy for correcting mistakes and reconstruction.

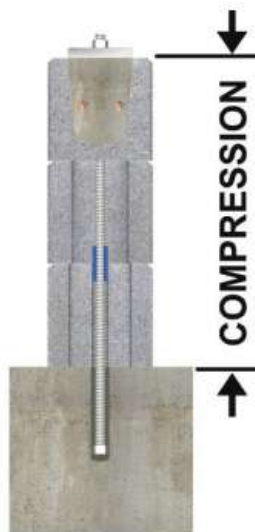


Fig 2.15 The FlexLock System - Wall System
(Source- The FluxLock System - Cercorp Initiatives Inc)

The system does not use grout or cement to hold the blocks or to reinforce the structure similar to other interlocking block systems. In the FlexLock system, a metal anti corrosive tendon runs through the blocks in vertical alignment to strengthen the structure and the block is held together with tendon by post-tension created by the tendons connected to the bearing plate at the end of wall height. Thus, there is no need for cement, slurry, water or other components which makes it one of the best system for design for deconstruction.

2.1.3.10. Azar Dry Stack Block

The Azar dry stack block, developed in Canada, is a mortar-less masonry wall system that has the interlocking provision in both horizontal and vertical directions. The block has hollow cells in which grout can be filled for enhancing axial load carrying capacity. The tongue and groove interlocking system helps in accurate alignment and quick placement.

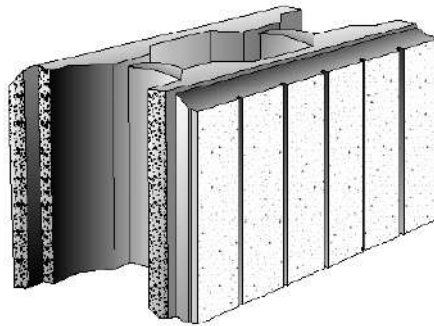


Fig 2.16 Azar Dry Stack Block

2.1.3.11. Mecano Block System

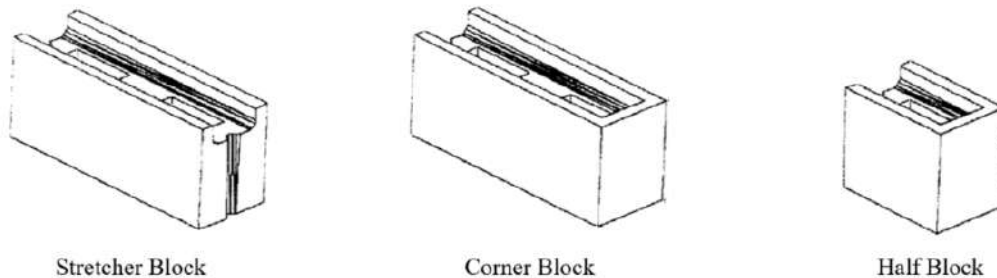


Fig 2.17 Mecano Block

Mecano block is developed in Peru by Cetholic in 1988. This interlocking block system has no interlocking mechanism and the blocks are simply stacked on top of each other to construct a wall. The block is made of sand and lime. The horizontal and vertical reinforcement can be used to interlock between the block unit with help from grouting into the hollow core of the blocks (Bosro, M. Z. M., Samad, A. A. A., Mohamad, N., Goh, W. I., Tambichik, M. A., & Iman, M. A. 2018, April).

2.1.3.12. Sillblock System

During the year 2000, Indian Institute of Technology, Madras developed solid interlocking block which was made out of concrete. IIT, Madras developed this system to accelerate the development of mortar-less masonry technology. The interlocking system consist of three units of varying shapes such as stretcher, jams and corner block. Dovetail design is used to create interlocking mechanism.

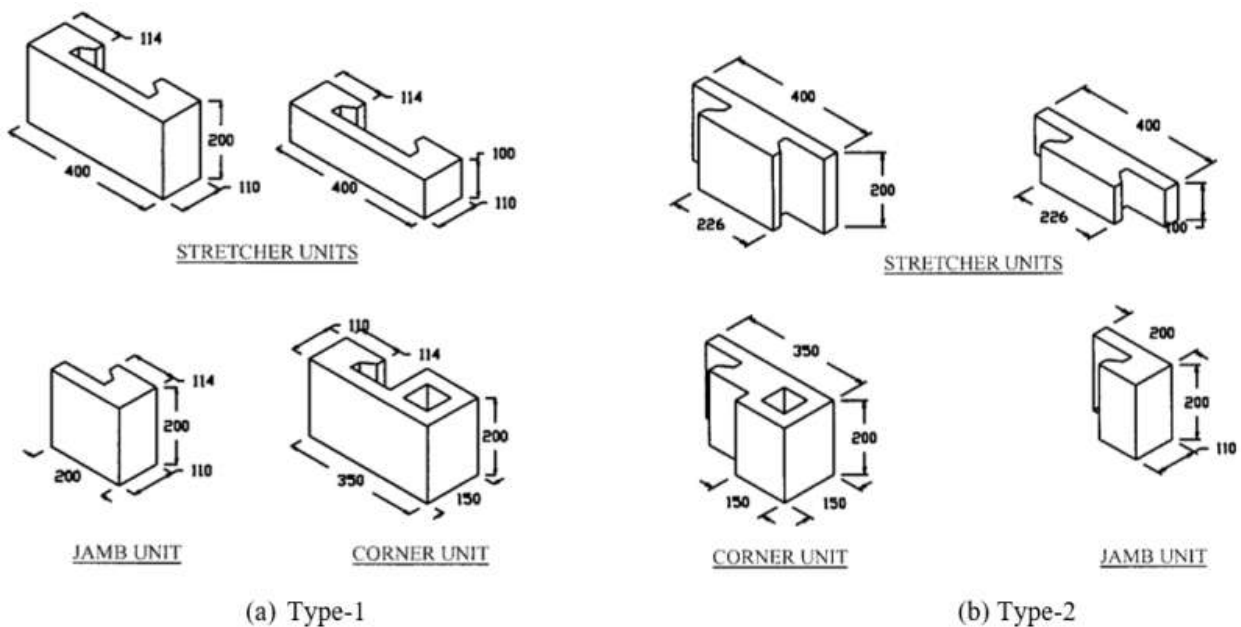


Fig 2.18 Sillblock System

2.1.3.13. Spar-lock System

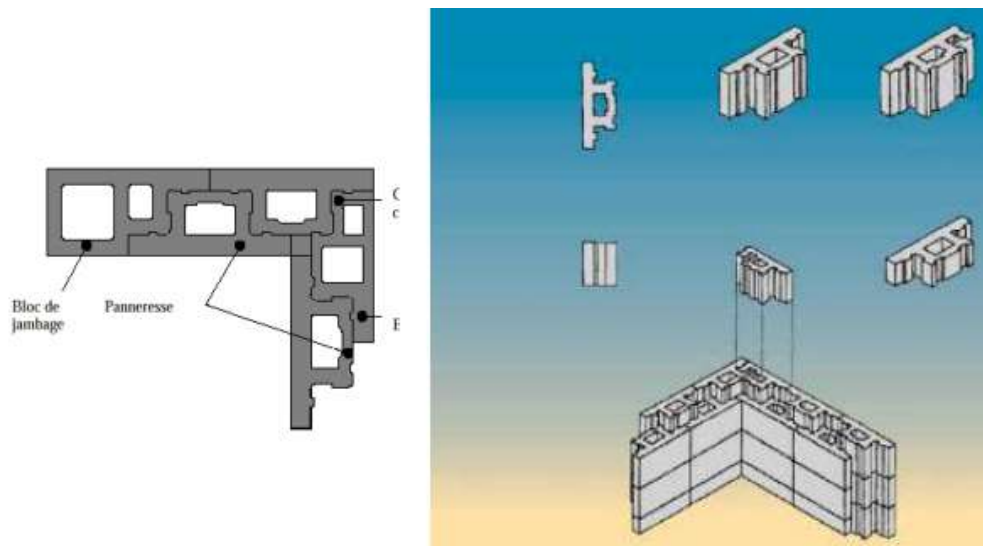


Fig 2.19 Spar-lock System

The Spar-lock system, uses unique shaped and specially designed blocks that slide together. The blocks are placed in a stack bond arrangement. The unique Spar-lock system is one feature that achieves interlocking of individual units in both the horizontal and vertical directions by use of built in shear keys. This system enables the interlocking to be continued around corners. Because the bed and head joints are not continuous straight through the wall there is no straight path for weather to penetrate to the other side of the wall. Spar-lock is not typically used in bearing wall situations but has been employed heavily on the firewall market. Vertical reinforcement and grout may be used but typically are not required for non-bearing situations (Fayez, M. K. M., 2015)

2.1.4. CLASSIFICATION OF INTERLOCKING BLOCKS

The mortar-less blocks can be classified into multiple types bases on certain categories based on their character. The main characters of the mortar-less blocks are,

- Material
- Interlocking Mechanism
- Geometry
- Locking Direction
- Reinforcement Type

These characters define the usage of the block. The interlocking blocks have different interlocking mechanisms similar to wood join

Table 2.2 Classification of Interlocking Blocks

Sl. No	Category	Character	Examples
1.	Material	Concrete	Haener, Sparlock, Mecano, Azar
2.		Sand, clay & Lime	Auram
3.		Stabilized mud	ISSB Thailand, ISEB Africa
4.	Interlocking Mechanism	Tongue and Groove	Haener
5.		Dove Tailed	Azar
6.		Lap	-
7.	Geometry	Hollow	Azar, Haener, Connex
8.		Solid	ISEB(Africa)
9.	Locking Direction	Horizontal	-
10.		Vertical	Alan, Hydraform, Solbrick
11.		Both horizontal & Vertical	Azar, Auram, Bamba, Haener, Sparlock
12.	Reinforcement Type	Horizontal	-
13.		Vertical	Sparlock, Auram, ISSB
14.		Both horizontal & Vertical	Haener, Mecano, Azar
15.		No Reinforcement	ISSB Africa

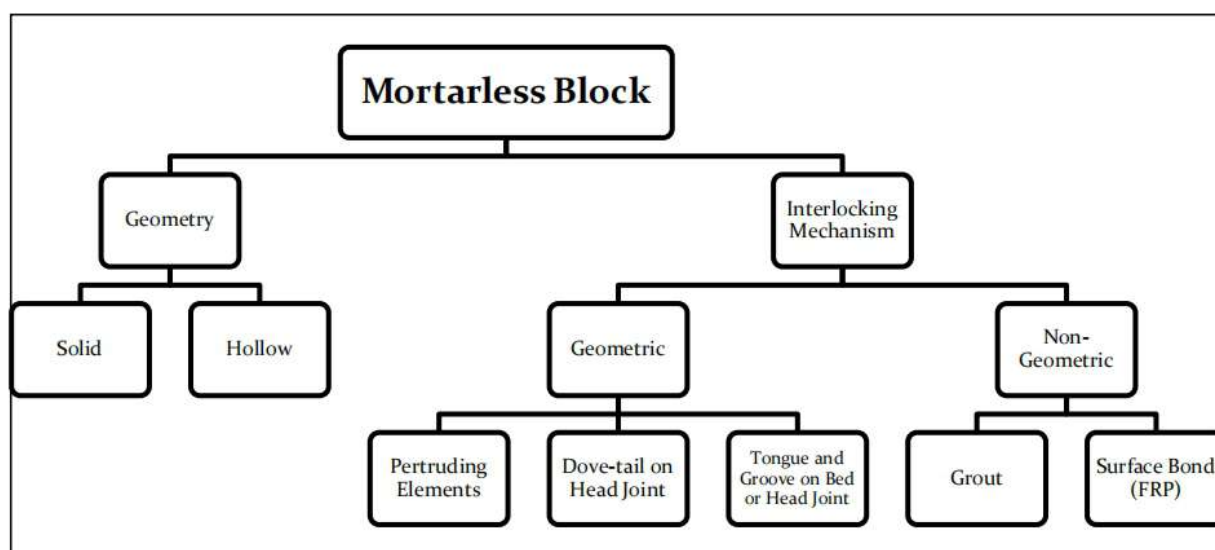


Fig 2.20 Classification of Block Mortarless Masonry
(Edwards, J., Gayed, M., Pyra, M., & Rodriguez, T., 2010, August)

2.1.5. PERFORMANCE OF INTERLOCKING BLOCKS

2.1.5.1. Basic Performance Requirements as per Standards

Initially to understand the performance of the interlocking blocks, the basic requirements and performance standards required for a masonry construction is studied. Indian standards and other codes, the baseline for brick and masonry blocks is studied.

A. IS 1905: 1987 code of practice for structural use of unreinforced masonry

As given in the study conducted by BIS on average strength achieved by a brick in various parts of India is as under:

➤ Delhi & Punjab	- 7 to 10 N/mm ²
➤ Uttar Pradesh	- 10 to 20 N/mm ²
➤ Madhya Pradesh	- 3.5 to 5 N/mm ²
➤ Maharashtra	- 5 N/mm ²
➤ Gujarat	- 3 to 10 N/mm ²
➤ Rajasthan	- 3 N/mm ²
➤ West Bengal	- 10 to 20 N/mm ²
➤ Andhra Pradesh	- 3 N/mm ²
➤ Assam	- 3.5 N/mm ²
➤ Ccutta & Madras	- 17.5 to 25 N/mm ²

The following relation generally holds good between strength of bricks and maximum number of storeys in case of simple residential buildings having one brick thick walls and rooms of medium size:

<u>N/mm²</u>	-	<u>Storey</u>
3-3.5	-	1 - 2
7	-	2 - 3
10	-	3 - 4
15	-	4 - 5

B. IS 1077 : 1992 common burnt clay building bricks - specification

After immersion in cold water for 24 hours, water absorption shall not be more than 20 percent by weight up to class 12.5 and 15 percent by weight for higher classes.

The dimensions of the burnt clay bricks in India is 190mmx90mmx90mm, 190mmx90mmx40mm, 230mmx110mmx70mm, 230mmx110mmx30mm.

C. As per Auroville Earth Institute - Disaster Resistance Structure

Interlocking blocks can resist disasters (Cyclones, earthquakes, tsunamis and floods), provided that they are hollow, so as to be reinforced with Reinforced Cement Concrete (RCC), at regular intervals. A hollow interlocking CSEB for earthquake resistance must satisfy these requirements:

- Extreme consistency in height (1 mm difference maximum is allowed).
Self-aligning to reduce time-wasting adjustments.
- Blocks should be hollow and the vertical holes and U shaped blocks should allow casting RCC, according to requirements: To reinforce regularly the masonry vertically and horizontally.
- The interlocking keys must interlock transversally and longitudinally to the wall. They should interlock especially well in the length of the wall, which is subject to the shear stress of the earthquake.
- Every course must interlock with each other as well as the header of every block in length: to increase the shear strength of the masonry.
- Good seating of the blocks on top of each other for properly transmitting the load bearing: All the block area, including the key, must transmit the load.
- The binder should be a cement-soil-sand (1: 1: 3) mortar of 5 mm thick. It should be quite fluid in order to be workable.
- The mould must allow manufacturing full size blocks and 3/4 and 1/2 sizes. The blocks must not be cut to match the bond pattern, which will be detrimental to the accuracy, strength and quality of the masonry.

2.1.5.2. Performance of Interlocking Blocks as per Existing Literature

As per the authors Adnan Bin Abdul Lateef and four others and their research on interlocking blocks, the interlocking solid block made from the composition of material such as Cement (20%), Gypsum (3%), Lime (2%) can perform better and efficient than conventional building materials. The authors created a new interlocking block model which is 12 inches in length, 4 inches in breadth and 8 inches height. The two rods of one brick interlock with the holes of the other bricks placed over them. This provides a joint between the bricks, it binds the bricks together. The binding and construction of the wall can be done

without using the cement (Lateef, A. B. A., Ashmi, S. M., Mannan, M. F. A., Ali, M. A., Hussaini, S. A., 2018).

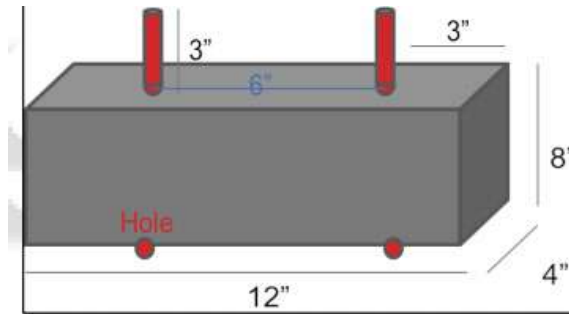


Fig 2.21 Interlocking Block

As per the authors, Compressive strength of interlock bricks are have ranges between 1.2 N/mm² to 2.0 N/mm² and they are very good for normal type of constructions like Partition walls, Boundary walls & non load bearing walls etc (Lateef, A. B. A., Ashmi, S. M., Mannan, M. F. A., Ali, M. A., Hussaini, S. A., 2018). The author has compared the interlocking block with other materials such as clay bricks, hollow concrete bricks, cement bricks. The results of the comparison is given in the table below.

Table 2.3 Interlocking Blocks - Comparison with Clay Bricks

Basic of Comparison	Clay Bricks	Inter-locking Block
Material Cost	Cheap	Normal
Construction Cost	Normal	Cheap
Time Rate	Slow	Fast
Building Temperature	Hot	Cool
Aesthetic Value	No	Yes
Labor required for construction	Skilled	Unskilled
Cement Usage for Construction	High	Low
Durability	Weak	Strong

Source: (Lateef, A. B. A., Ashmi, S. M., Mannan, M. F. A., Ali, M. A., Hussaini, S. A., 2018)

Table 2.4 Interlocking Blocks - Comparison with Cement Bricks

Basic of Comparison	Cement Bricks	Inter-locking Block
Material Cost	Normal	Normal
Construction Cost	Expensive	Cheap
Time Rate	Slow	Fast
Building Temperature	Normal	Normal
Aesthetic Value	No	Yes
Cement Usage for Construction	High	Low
Durability	Strong	Normal

Source: (Lateef, A. B. A., Ashmi, S. M., Mannan, M. F. A., Ali, M. A., Hussaini, S. A., 2018)

Table 2.5 Interlocking Blocks - Comparison with Concrete Hollow Bricks

Basic of Comparison	Concrete Hollow Bricks	Inter-locking Block
Material Cost	Expensive	Cheap
Construction Cost	Expensive	Cheap
Time Rate	Slow	Fast
Building Temperature	Hot	Cool
Aesthetic Value	No	Yes
Labor required for construction	Skilled	Unskilled
Cement Usage for Construction	High	Low
Durability	Normal	Normal

Source: (Lateef, A. B. A., Ashmi, S. M., Mannan, M. F. A., Ali, M. A., Hussaini, S. A., 2018)

Another comparative analysis is also carried out by Adrian Perez, comparing interlocking blocks with other masonry blocks. This study was carried out using African building blocks under the assistance of UN Habitat. The Interlocking Stabilized Soil Blocks are compared with other conventional materials such as sun dried mud blocks, burnt clay bricks, stabilized soil blocks and concrete masonry units. The inference of the comparison is given in the table below:

Table 2.6 Interlocking Blocks - Comparison with other Bricks

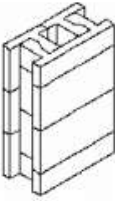
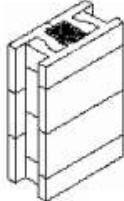
Properties	Interlocking Stabilised Soil Block	Sun-dried Mud Block	Burned Clay Brick	Stabilised Soil Block b	Concrete Masonry Unit
GENERAL INFO					
Block Appearance					
Wall Appearance (not rendered)					
Dimension (L x W x H) (cm)	26.5 x 14 x 10 cm	25 x 15 x 7 cm to 40 x 20 x 15	20 x 10 x 10 cm	29 x 14 x 11.5 cm	40 x 20 x 20 cm
Weight (kg)	8-10 kg	5-18 kg	4-5 kg	8-10 kg	12-14 kg
Texture	Smooth and flat	rough and powdery	rough and powdery	smooth and flat	coarse and flat
Blocks needed to make up a sq.m.	35	10 to 30	30	21	10
PERFORMANCE					
Wet Compressive Strength (mps)	1 - 4	0 - 5	0.5 - 6	1 - 4	0.7 - 5
Thermal Insulation (W/m C)	0.8 - 1.4	0.4 - 0.8	0.7 - 1.3	0.8 - 1.4	1 - 1.7
Density (kg/m ³)	1700 - 2200	1200 - 1700	1400 - 2400	1700 - 2200	1700 - 2200
AVG. PRICE (2009)					
Per Block (UgS)	350	50	150	400	3000
Per Sq Meter	35000	10000	55000	45000	75000

Source: (Perez, A., 2009)

The authors K. B. Anand and K. Ramamurthy also conducted experiments on IITM-HILBLOCK (Hollow Inter-Locking BLOCK) developed at Indian Institute of Technology, Madras. The HILBLOCK system can be adopted for ungrouted or partially/fully grouted (that is either plain (non-reinforced) or reinforced with vertical and/or horizontal reinforcement) construction. HILBLOCK masonry facilitates grouting to cater to structural requirements although grouting is not required for constructional stability (Anand, K. B., & Ramamurthy,

K., 2005). The authors conducted the evaluation on the structural performance of the unreinforced (ungrouted and grouted) HILBLOCK masonry under concentric, eccentric, and flexural loading.

Table 2.7 Specimen Details and Test Results of Axial Compression
(Anand, K. B., & Ramamurthy, K., 2005)

Block strength = 10.71 MPa		Grout strength = 11.84 MPa			
Description		Type of construction			
		Ungrouted		Grouted	
Specimen size - 400mm long; 600mm high					
Type of bedding		Dry-stacked	Thin-jointed	Dry-stacked	Thin-jointed
Prism strength on net area (MPa)	Mean of 6 specimens	6.69	8.84	7.28	9.15
	CoV	0.126	0.093	0.089	0.077
Efficiency factor (Prism/block strength)		0.62	0.83	0.68	0.85
Allowable stresses on gross area (MPa)		1.25	1.66	1.66	2.08
CoV = Coefficient of variation					

The table 2.7 shows that the prism strength is achieve 9.15 MPa in grouted thin jointed interlocking system. It can be understood that the internal grouting on the hollow interlocking blocks can increase the strength of the wall construction. It can also be noted that adding thin joints to the interlocking blocks can also increase its strength compared to the dry stacked blocks.

As per the research conducted by the authors M Z M Bosro, A A A Samad, N Mohamad, W I Goh, M A Tambichik and M A Iman from Jamilus Research Center, University Tun Hussein Onn Malaysia, the investigations of masonry unit such as the Putra Block was conducted and analysed and the results of the analysis is given below.

Table 2.8 Compressive strength test of individual Putra block units
(M Z M Bosro., et al, 2018)

Types of specimens	Density, P (kg/m ³)	Compressive strength (N/mm ²)	Tensile strength, f_t (N/mm ²)
Stretcher	2042.24	18.62	2.06
Corner block	2014.8	18.02	2.79
Half block	1936.66	17.03	2.16
Grout	2035.00	15.00	2.09
Reinforcement	-	-	$f'_y = 275$

As per the research conducted by Harshad M. Patel, Tejas J. Upadhyay and Dr. N.K. Arora, The compressive test, shake table test and other tests are conducted between conventional blocks and interlocking blocks to analysis the strength of both the blocks.



Fig 2.22 Setup for Compression Test



Fig 2.23 Setup for Flexural Loading Test



After the compression test (Fig 2.22), the compressive strength of interlocking masonry was found to be 10.107 N/mm^2 . The stress strain relationship of the interlocking blocks was found to be bi-linear. As the loading of compression increases, the interlocking blocks initially try to settle inbetween gaps and irregularities. However, as the loading increases, the interlocking blocks starts to deform (Patel, H. M., Upadhyay, T. J., & Arora, N. K., 2003).

In the flexural load testing experiment (Fig 2.23), load was applied at a gradual rate of 0.125 mm per minute. The results showed that the flexural tensile strength of interlocking block masonry is higher then that of the conventional masonry. From the experiments conducted by the authors, the compressive strength of the interlocking blocks (10.107 N/mm^2) is greater that that of the conventional masonry (8.71 N/mm^2). The initial deformation of the interlocking blocks is very high. The interlocking blocks perform better and can carry the lateral loads better and absorb more energy that conventional masonry before failure (Patel, H. M., Upadhyay, T. J., & Arora, N. K., 2003).

2.1.6. PROPERTIES OF INTERLOCKING BLOCKS

The interlocking blocks are different from conventional bricks since they do not require mortar to be laid during bricklaying work. Because of this characteristic, the process of building walls is faster and requires less skilled labour as the blocks are laid dry and lock into place. Concrete blocks may be produced with hollow centers to reduce weight, avoid seepages or improve insulation. The holes inside the concrete block allow rebar and concreting (creating reinforced concrete) to run vertically through the block to compensate

for the lack of tensile strength. Rebar used can be of mild steel instead of the usual higher grade steel. Once a section of wall is built, grout holes are filled with a lean cement mixture to seal the wall and making a permanent solid wall. The amount of grout used was calculated to be less than 7.5% of the mortar used in conventional masonry.

The general properties of the interlocking blocks are as follows:

- i. Since the blocks can be laid dry, no mortar is required and a considerable amount of cement is saved.
- ii. Each block has vertical holes, which serve four purposes:
 1. To reduce the weight of the block,
 2. To insert steel rods or treated kenaf bar for reinforcement,
 3. To act as conduit for electrical and water piping,
 4. To pour liquid mortar (grout) into the holes, which run through the full height of the wall, thus increasing its stability and providing barrier to seepages.
- iii. The length of each block is exactly double its width, in order to achieve accurate alignment of blocks placed at right angles; else, a junction block is required.

2.1.6.1. Advantages of Mortarless Construction

Table 2.9 Advantages of Mortarless Construction

Sl.No	Advantages	Reference
1.	Blocks can be laid much easier with less technical skill.	(Edwards, J., Gayed, M., Pyra, M., & Rodriguez, T., 2010, August)
2.	Decreased risk of moisture damages and shrinkage	
3.	More stability during construction (especially for interlocking blocks) compared with conventional masonry because the blocks do not “swim” in mortar	
4.	Walls can be loaded immediately after construction	
5.	Masonry can be assembled in any weather conditions (i.e. winter season).	
6.	elimination of bedding mortar will accelerate construction, thereby reducing cost and variation due to workmanship	
7.	Density of masonry can be reduced in the range of 13 – 17	(Deepak, B., 2012)

	kN/cum against the conventional fired brick system (19.20 kN/cum) in terms of unit weight.	
8.	High finish blocks are made; result in exposed finish aesthetic walls, saving on plaster/rendering & finishes.	
9.	Blocks can be made with lower water absorption properties making them useful for even relatively wet applications.	
10.	Blocks can be made with reinforcement / conduit features facilitating earthquake resistant construction	
11.	Blocks made are eco friendly as no burning is involved	
12.	Health - The curved ISSB can make water tanks, lining for pit latrines, and septic tanks. The final cylindrical shape and interlocking mechanism resists well against water pressure.	(Perez, A., 2009)
13.	Environment - alternative to fired brick, Eco-friendly	
14.	Economical - affordable way of construction, brick weatherproof so no need to plaster, due to its interlocking mechanism little cement is needed, quick construction allowing for labor savings, The machine weighs 140kg making it easy to transport and work onsite	
15.	Educational - new technology, increase local skills, income-generating opportunity, easy to learn	
16.	Structural - strong and durable when compared with traditional method, good compressive strength, used for the retaining wall of buildings.	
17.	Aesthetic - aesthetic qualities not foreign to local communities	
18.	Easy to use - The ISSB machine easy to use and to maintain. After long use, repairs can be made locally through scrap material and welding. Due to the interlocking mechanism of the blocks, wall construction is much easier and quicker.	

2.1.6.2. Limitations of Mortarless Construction

Table 2.10 Limitations of Mortarless Construction

Sl.No	Limitations	Reference
1.	Set mortar was required at the base of a wall in order to facilitate wall levelling and aligning for the first course.	(Edwards, J., Gayed, M., Pyra, M., & Rodriguez, T., 2010, August)
2.	Relatively high initial settlement.	
3.	Challenges in controlling the height of the units to achieve accurate running bond.	
4.	Difficulty in keeping grooves from breaking during transportation and construction.	
5.	In running bond pattern, plain interlocking units without grouting have little resistance to vertical bending.	
6.	In stack bond pattern, plain interlocking units without grouting have little resistance to horizontal bending.	
7.	Wall construction must be fully grouted in several projects	
8.	Exterior above-grade walls and interior load bearing walls are limited to a height no greater than 20 times the wall thickness.	

2.1.6.3. Productivity of Mortarless Construction

In a study done by Ramamurthy and Nambiar in 2004, it was found that the rate of construction can be accelerated significantly. The laboratory experiment involved the construction of 1400 mm square panels from both conventional block masonry and Whelen interlocking block masonry. Test results showed that the completion time for the conventional masonry was 3.5 hours with a crew of one person, whereas the time spent for the Whelen blocks was 1.25 hours. This indicates that the production rate for the mortarless system is approximately 4.1 m² per hour, which is 2.5 times that of the traditional system. Manufacturers of Haener blocks state that their system allows blocks to be laid up to five times faster than conventional block masonry, creating labour savings up to 80%. With the Azar system, the Azar group reports that unskilled workers can stack 100 blocks each per hour, compared with approximately 30 to 40 blocks per hour for a crew of three masons and one helper for conventional masonry (Edwards, J., Gayed, M., Pyra, M., & Rodriguez, T., 2010, August), (Ramamurthy, K., & Kunhanandan Nambiar, E. K., 2004).

Table 2.11 Time Taken Analysis

Task	Type	Time Taken	Crew
Construction of 1400mm square panel	Conventional block masonry	3.5 Hours	1 Person
	Whelan interlocking Blocks	1.25 Hours	

As per an other comparative study of interlocking and sandcrete Blocks for building walling systems by Sampson Assiamah , Herbert Abeka, Stephen Agyeman, it was deduced that for the first course, the sandcrete block wall was constructed at an average speed of 1.34 times faster than the interlocking. For the other courses, interlocking block wall was constructed at an average speed of 4.40 times faster than the sandcrete for the second course, 2.58 faster for the subsequent courses after the first, and 2.09 faster for the completion of the entire wall. These indicate that the pace of wall construction using the interlocking blocks is always faster than using the sandcrete block. The elimination of non-value steps like spreading mortar, levelling, and vertical mortar jointing and dressing of joints significantly reduced the cycle time of bonding blocks thus increasing the speed of the wall construction (Assiamah, S., Abeka, H., & Agyeman, S., 2016).

Table 2.12 Time Taken Analysis

Technique	Mason	1 st Course (minutes)	2 nd Course (minutes)	Subsequent Courses (minutes)	Entire wall (minutes)
Sandcrete block	X	21	23	133	177
	Y	20	21	135	176
Interlocking block	X	27	5	52	84
	Y	28	5	52	85

Source: (Assiamah, S., Abeka, H., & Agyeman, S., 2016)

2.1.6.4. Cost Comparison of Mortarless Construction

The authors *Edwards, J., Gayed, M., Pyra, M., & Rodriguez, T* has compared the cost expenditure of the conventional masonry system with Azar mortarless construction system and derived the results. The results shows that in a traditional construction the cost for material to labour ration is 40:60 respectively. The Azar system has higher material cost than the traditional system. However, the cost required for labour is reduced considerably, thereby reducing the overall construction cost of the building. The labour cost for interlocking construction is only 1/4th of that of the traditional construction. It can be understood that, even if the cost of the interlocking blocks are higher than that of the traditional building material, the cost saving can be achieved through labour cost savings.

This reduced the overall cost of the project, making the mortarless system a cheaper form of construction than traditional system.

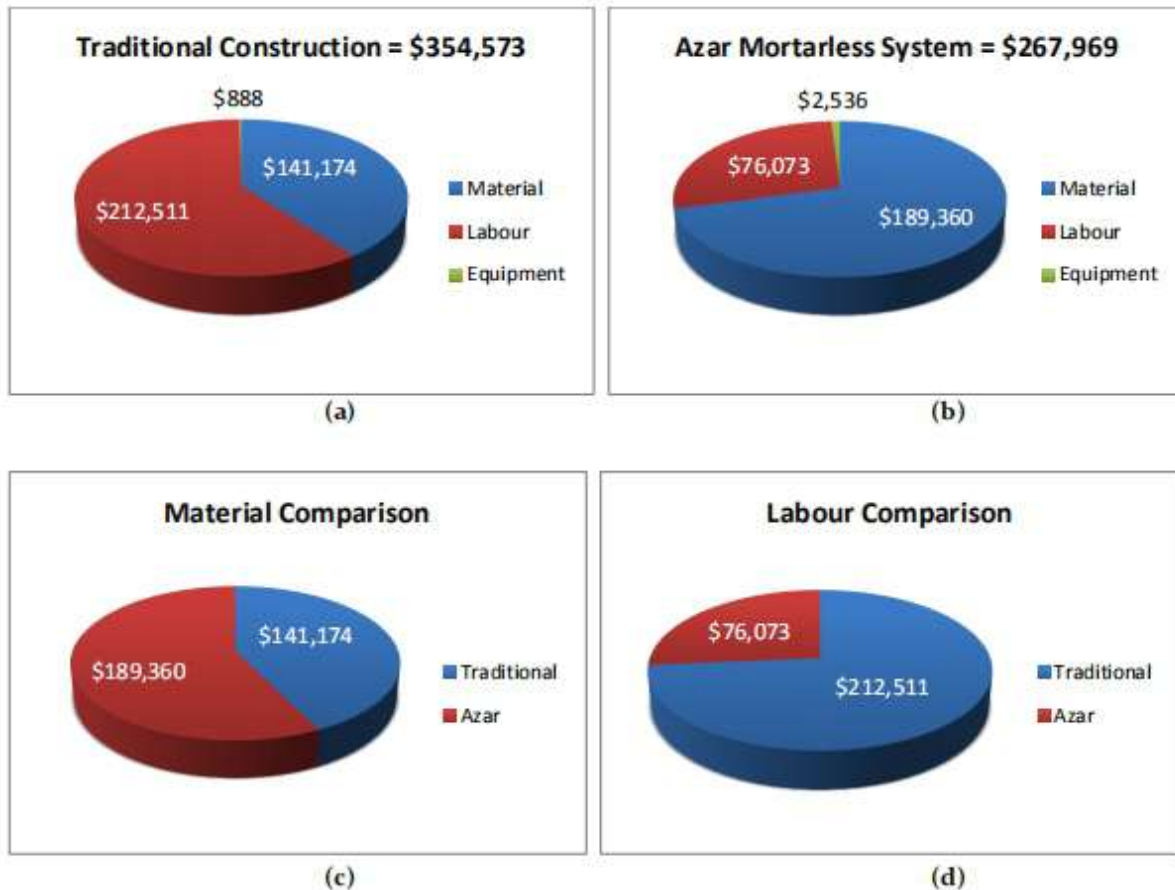


Fig 2.24 Construction costs associated with traditional and Azar mortarless Construction
(Edwards, J., Gayed, M., Pyra, M., & Rodriguez, T., 2010, August)

Another researchers has also conducted a cost comparison analysis among interlocking hollow blocks and typical RCC construction. The authors Mahmood Md. Tahir, Anis Saggaff, Shek Poi Ngian, Arizu Sulaiman has analysed savings from the use of IHBS their paper by comparing the construction of two storey terrace house with build-up area of about 200 square meter with conventional construction method of typical reinforced concrete construction (RCC) compared to IHBS. The comparison shows that the implementation of IHBS can reduce construction time, cost, and utilization of man power up to 26.6% compared to the conventional method. Moreover, the construction time using IHBS can also be reduced by up to 50% as compared to the conventional construction (Tahir, M. M.,

Saggaff, A., Ngian, S. P., & Sulaiman, A., 2017, November). The interlocking hollow brick system that is used for comparison is shown in fig 2.25 below.

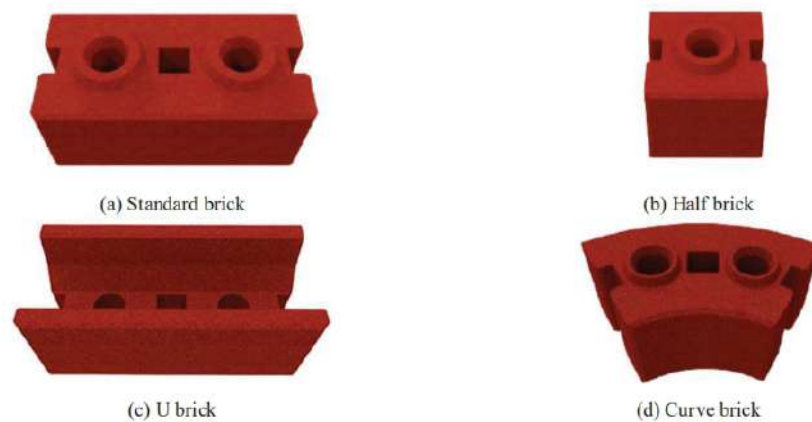


Fig 2.25 Interlocking Hollow Brick System
(Tahir, M. M., Saggaff, A., Ngian, S. P., & Sulaiman, A., 2017, November)

In this study, it can be concluded that the cost associated with the process of constructing a wall with the interlocking block is far lower compared to using the conventional block. Despite the fact that a relatively lower cost of labour played a role as the use of IHBS did not require the construction of formwork for beam, column, and slab. The design concept of IHBS as load bearing has significantly reduce the need of labor as the wall can be functioned as column and beam. the study also revealed that a number of non-value added steps like spreading of base mortar for various courses, vertical mortar jointing and levelling, which are associated with the use of conventional block, could be eliminated when the interlocking block is used for wall construction. Such various forms of waste as over-production, unnecessary movement, unnecessary processing, inventories and waiting, seen to be associated with the use of the conventional blocks, are minimized to a large extent when the interlocking block is in use. The elimination of the various non-value added steps associated with the conventional block wall construction can also be identified through the use of the interlocking block system by reducing the cycle time of block bonding thus increasing the speed of wall construction. There is also a significant reduction in the material requirement for the interlocking block wall construction process due to the absence of mortar jointing. Reduction in the labor and material requirements in the interlocking block wall construction process makes the cost associated with the process of building walls using the interlocking blocks far less.

Table 2.14 Cost comparison of construction using IHSB vs RCC

Cost comparison of construction using IHSB vs RCC		
Construction activities		Cost (Malaysian Ringgit)
A	Conventional Construction - Cost calculated based on the following construction activities	485605.00
1.	External Works – Earthwork, site clearance, mobilization, setting grid lines	
2.	Sub-structures – Excavation and fill, concreting, preparing formwork, layout on rebars.	
3.	Beams, columns and slabs – Concreting, preparing formwork, layout on re-bars	
4.	Brickworks and plastering – Plaster on both sides, skin coating	
5.	Transportation and machineries	
6.	Roof trusses, windows, doors, plumbing and accessories	
7.	Drainage and sewerage	
8.	Wiring, painting, and site clearance	
9.	Design and endorsement	
B	Interlocking brick system - Cost calculated based on the following construction activities	377515.00
1.	External Works – Earthwork, site clearance, mobilization, setting grid lines	
2.	Sub-structures – Excavation and fill, concreting, preparing formwork, layout on rebars	
3.	Ground Beams and slabs – Concreting, preparing formwork, layout on re-bars	
4.	Brickworks and mortaring – Lay the IHBS and filled with mortar	
5.	Transportation and machineries	
6.	Roof trusses, windows, doors, plumbing and accessories	
7.	Drainage and sewerage	
8.	Wiring, painting, and site clearance	
9.	Design and endorsement	
Saving in labor = [6 workers x 6 months(conventional) – 6 workers x 3 months (interlocking brick)] 26days x 3 x RM100 x 6 {Saving in labor by 50%}		46,800
Saving in construction material		61,290
Total direct saving = 485,605.00 – 377515 = 108,090.00		
Saving due to 3-month completion which can be converted to renting (2,000 x 3 month)		6,000
Saving on crane for concreting column and roof beam		2,000
Saving due to site clearance and dumping of construction waste		3,000

Saving due to defect and maintenance	10,000
Total indirect saving	21,000
Total direct and indirect saving % difference = $[(485605 - 377515) + 21000 / 485,605] \times 100\% = 26.6\%$	

Source: (Tahir, M. M., Saggaff, A., Ngian, S. P., & Sulaiman, A., 2017, November)

As per an other comparative study of interlocking and sandcrete Blocks for building walling systems by Sampson Assiamah , Herbert Abeka, Stephen Agyeman, cost associated with the process of constructing a wall with the interlocking blocks and the conventional sandcrete blocks is calculated. Labor cost was calculated at a rate of Gh¢5.00/hr. and material cost at a rate of Gh¢400.00/m³ of mortar.

Table 2.15 Cost of wall construction

a. Labor Cost					
Item	Description	Conventional block		Interlocking block	
		Average Time per mason (hr.)	Approximate labor cost @ Gh¢5.00/hr.	Average Time per mason (hr.)	Approximate labor cost @ Gh¢5.00/hr.
1.	Building first course	0.35	1.75	0.46	2.30
2.	Spreading mortar for subsequent courses	0.54	2.70	0.00	0.00
3.	Placing blocks, levelling and plumbing	1.10	5.50	0.95	4.75
4.	Filling and dressing vertical mortar joints	0.95	4.75	0.00	0.00
5.	<i>Total labor cost</i>	<i>2.94</i>	<i>14.70</i>	<i>1.41</i>	<i>7.05</i>
b. Material Cost					
Item	Description	Conventional block		Interlocking block	
		Quantity (m ³)	Approximate mortar cost @ Gh¢400.00/m ³	Quantity (m ³)	Approximate mortar cost @ Gh¢400.00/m ³
1.	Mortar	0.62	248.00	0.05	20.00
2.	<i>Total material cost</i>		<i>248.00</i>		<i>20.00</i>
c.	Total Cost of Wall Construction		262.70		27.05

Source: (Assiamah, S., Abeka, H., & Agyeman, S., 2016)

2.1.6.5. Earthquake Resistance of Mortarless Construction

The mortarless construction has compatibility for reinforcement for earthquake resistant construction. The interlocking blocks can be easily reinforced (because of the grooves) against the conventional masonry. All the relevant bands i.e. roof bands, gable band, lintel band, cill band and plinth band etc. can be easily incorporated in the masonry (as per the requirements of the seismic design). Both vertical and horizontal Reinforcement can be

provided by means of the grooves. The sizes of the grooves can be increased also (Deepak, B., 2012).

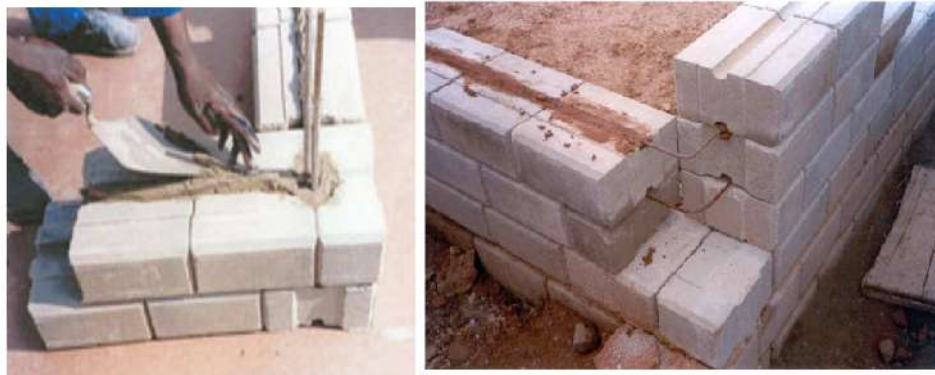


Fig 2.26 Vertical and Horizontal Reinforcement for Earthquake Resistant Construction
(Deepak, B., 2012)

2.1.6.6. Reinforced Interlocking Blocks Column

In the research conducted by Yeong Huei Lee, Poi Ngian Shek, Shahrin Mohammad on studying the structural performance of the reinforced interlocking block column, inter-locking blocks have been innovatively assembled as columns for developing a new system that can replace the conventional concrete construction to block construction, without concrete beams and columns. These interlocking block columns are tested in the laboratory in order to investigate their structural performance under axial load (Lee, Y. H., Shek, P. N., & Mohammad, S., 2017).

With reference to BS EN1996-1-1, masonry structural design, the design of a reinforced wall and beam are described. There is no clear design guide on reinforced interlocking block columns. Author derived new formula for interlocking block column design and conducted experiments to test the strength and axial load carrying capacity of the column.

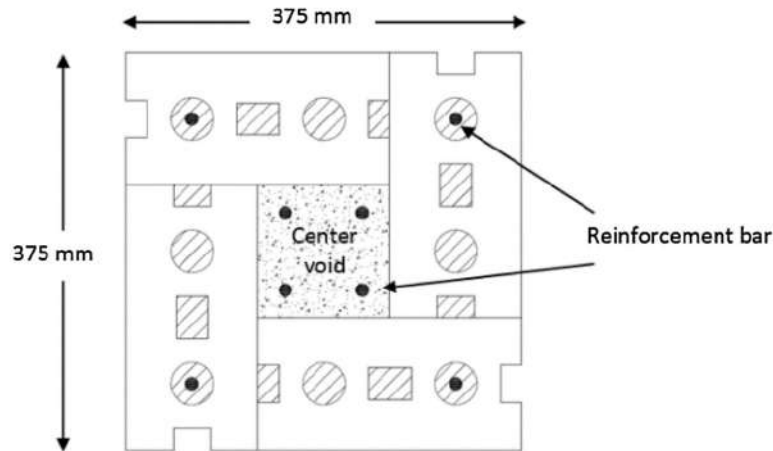


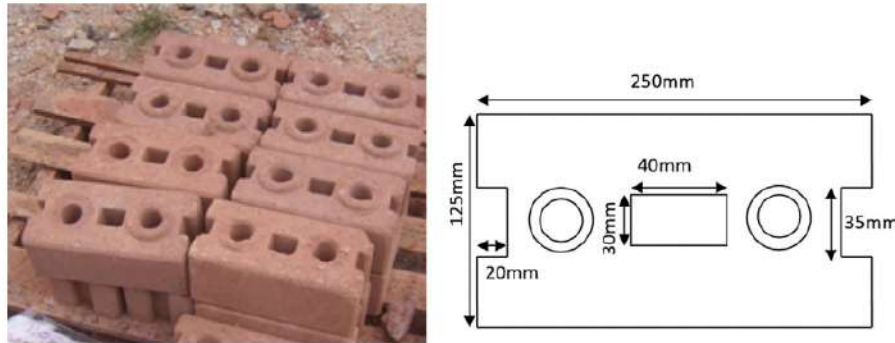
Fig 2.27 Section of Constructed Column
(Lee, Y. H., Shek, P. N., & Mohammad, S., 2017)

Table 2.16 Benefits of Interlocking Construction
(Lee, Y. H., Shek, P. N., & Mohammad, S., 2017)

Attribute	Reinforced concrete (RC)	Interlocking block system
Speed	Curing time required and highly depend on the local weather	30–40% faster than RC
Formwork	Timber or steel formwork is required	Minimum formwork required where eliminate 50–75% beam and column formworks
Worker	Skilled workers for plastering works, carpenters and bar-benders	Reduce skilled workers
Cost	Cost highly depend on skilled workers	Cost can be reduced from formwork, skilled workers and construction time
Waste	Timber waste from formwork	Less waste than RC construction
Quality	Quality highly depends on workmanship	Blocks are quality controlled by factory manufacturing

Mortar Type M and S are used. These two mortars will be applied to the filler of the interlocking blocks. There were two grades of concrete, C25 and C30 applied in this research, as referred to mix design by British Research Establishment. The interlocking blocks were supplied by the Arca Klasik Group, Malaysia. These blocks are claimed to be

environmental friendly as they do not required a baking process, thus reducing the carbon footprint in the construction industry. There were two types of reinforcement bars, Y12 and R6. The main reinforcement bar is a high tensile bar of Y12 with a diameter of 12 mm; whereas the shear link is an R6, mild steel bar with 6 mm diameter.



**Fig 2.28 interlocking blocks by the Arca Klasik Group, Malaysia
(Lee, Y. H., Shek, P. N., & Mohammad, S., 2017)**

**Table 2.17 Concrete Mix Calculation
(Lee, Y. H., Shek, P. N., & Mohammad, S., 2017)**

Stage	Item	Mix Design	
		25 N/mm ²	30 N/mm ²
Free water-cement ratio determination	Characteristic strength	25 N/mm ² at 28-days with proportion defect of 5%	30 N/mm ² at 28-days with proportion defect of 5%
	Standard deviation	8 N/mm ²	8 N/mm ²
	Margin (k = 1.64)	13.12 N/mm ²	13.12 N/mm ²
	Target mean strength	38.12 N/mm ²	43.12 N/mm ²
	Cement type	Ordinary Portland Cement	Ordinary Portland Cement
	Type of coarse aggregate	Crushed	Crushed
	Type of fine aggregate	Crushed	Crushed
Free water content determination	Free water-cement ratio	0.54	0.52
	Slump or vebe time	Slump = 20 mm	Slump = 20 mm
	Maximum aggregate size	20 mm	20 mm
Cement content determination	Free water content	190 kg/m ³	190 kg/m ³
Cement content determination	Cement content	352 kg/m ³	365 kg/m ³
Total aggregate content determination	Relative density of aggregate (SSD)	2.65	2.65
	Concrete density	2400 kg/m ³	2400 kg/m ³
	Total aggregate	1858 kg/m ³	1845 kg/m ³
Fine and coarse aggregates determination	Grading	40% passing through 600 µm sieve	40% passing through 600 µm sieve
	Proportion of fine aggregate	47%	47%
	Fine aggregate content	909 kg/m ³	867 kg/m ³
	Coarse aggregate content	949 kg/m ³	978 kg/m ³

Table 2.18 Properties of Mortar and Grout
(Lee, Y. H., Shek, P. N., & Mohammad, S., 2017)

Properties	Mortar									Grout
	Type M					Type S				
Water-cement ratio	0.5**	0.6	0.7	0.8	0.9	0.9	1.0	1.1	1.2	4 L*
Density, kg/m³	2200	2110	2085	2070	2040	2030	2005	2015	2015	2170
Flow table, mm	–	18.25	21.63	24.63	>25	20.75	23.88	>25	>25	>25
Inverted slump spread, mm	–	–	334	469	495	–	345	448	529	> 600

* 4 litre water for 25 kg of SikaGrout®-215.

** In this water-cement ratio, flow table and inverted slump tests were not able to be performed.

Table 2.19 Material Properties
(Lee, Y. H., Shek, P. N., & Mohammad, S., 2017)

No.	Compressive Strength (N/mm ²)									
	Grout	Mortar M		Mortar S		IB	C25		C30	
	28d	7d	28d	7d	28d		7d	28d	7d	28d
1	68.92	5.20	5.87	6.43	6.46	14.34	20.96	24.99	23.86	36.21
2	58.91	5.36	6.75	5.73	5.56	14.47	20.82	24.09	21.54	32.96
3	69.57	5.71	6.71	5.51	5.84	14.02	20.90	26.56	20.43	27.56
Mean	65.80	5.42	6.44	5.89	5.95	14.28	20.89	25.21	21.94	32.24

IB = Interlocking blocks.

7d = 7 days of water curing.

28d = 28 days of water curing.

Material tests involved a compressive test of grout, mortar, concrete and interlocking blocks. Compression tests (with cube dimension of 50 x 50 x 50 mm) for Sika Grout-215 were carried out at the grout age of 28-days in water curing. The difference of mean of 65.80 N/mm² and design strength of 67.50 N/mm² was insignificant in strength comparison.

In order to maintain the flowability of these mortars, a high water to cement ratio was used. As a result, lower compressive strengths for mortar Type M and S were obtained. Two different strengths of concrete cubes are prepared, 25 N/mm² and 30 N/mm². The cube dimension was 100 x 100 x 100 mm. The results of a compressive strength test on interlocking block units tested at 28 days strength have been recorded. Every sample failed due to crushing of interlocking blocks. The mean value of 14.28 N/mm² would then be used as the characteristic strength of interlocking blocks.

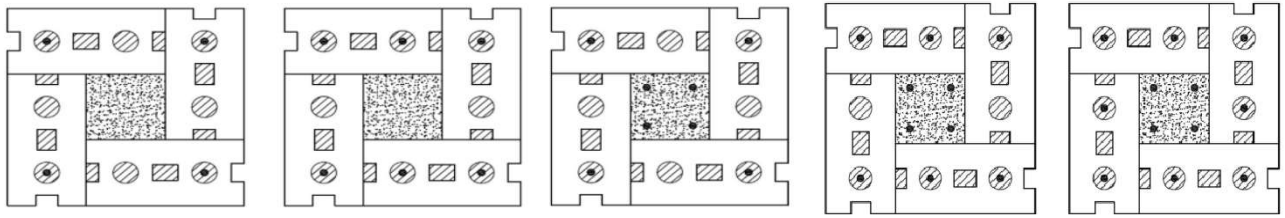


Fig 2.29 Arrangement of Reinforcement Bar - 4Y, 6Y, 8Y, 10Y, 12Y
(Lee, Y. H., Shek, P. N., & Mohammad, S., 2017)

The construction of the reinforced column using interlocking block is carried out in steps that was explained below (Bredenoord, J., al. Et, 2019):

1. The corner blocks are arranged and the vertical reinforcement are done.
2. The interlocking blocks are arranged along the reinforcements.
3. The vertical reinforcement holes are filled with cement grout.



Fig 2.30 Making of Reinforced Column using Interlocking Block
(Bredenoord, J., al. Et, 2019)

2.1.7. SELF ALIGNMENT OF INTERLOCKING BLOCKS

Self-interlocking blocks can be defined as the blocks which are locked against each other with help of groves without the use of cement mortar to form a structurally stable partition wall. These bricks will have inherent projecting parts, which fit exactly into depressions in the adjoin bricks placed aside, such that they are automatically aligned horizontally and vertically - thus bricklaying is possible without special masonry skills. It does not demand mortar for construction & plastering to conventional extent. This system aspires to reduce the material & labor cost of partitioning of space and speed up the construction (Shikalgar, J. N., & Kate, R. G., 2020).

2.1.8. DRY WALL CONSTRUCTION USING INTERLOCKING BLOCKS

The interlocking block wall construction do not use mortar for the wall construction except in the first course. The rest of the courses are laid as dry stacked construction. From the table 2.20, it can be understood that the construction of conventional wall require spreading of base mortar, filling and dressing of vertical mortar joints for all the courses. The construction of the wall using interlocking blocks do not need mortar for filling and dressing of vertical mortar joints for all the courses and spreading the mortar for setting the base of every course except the first course.

Table 2.20 Steps involved in walls construction

Stage	Description	Activities (Steps)	Sandcrete Block Walling	Interlocking Block Walling
A	General (Preliminary) Preparation	A1. Setting out	•	•
		A2. Preparation of mortar	•	•
		B1. Transporting mortar	•	•
B	Laying First Course	B2. Spreading base mortar	•	•
		B3. Transporting block units	•	•
		B4. Placing block units in first course	•	•
		B5. Plumbing	•	•
		B6. Levelling	•	•
		B7. Filling and dressing vertical mortar joints	•	○
		C1. Transporting mortar	•	○
C	Laying Subsequent Courses	C2. Spreading mortar for the course	•	○
		C3. Transporting block units	•	•
		C4. Placing block units in the course	•	•
		C5. Plumbing	•	•
		C6. Levelling	•	○
		C7. Filling and dressing vertical mortar joints	•	○

Source: (Assiamah, S., Abeka, H., & Agyeman, S., 2016)

2.2. PRODUCTION OF INTERLOCKING EARTH BLOCKS

2.2.1. Manual Interlocking Stabilised Soil Block Machine

The Interlocking stabilised soil block is produced using ISSB technology in Africa (Perez, A., 2009). In East Africa, the manual Interlocking Stabilised Soil Block machine is manufactured in Kenya. The main function of the machine is soil compression. Block quality

is not so much defined by the machine but by the quality of the raw materials introduced into the mould, the method used for mixing them and the moisture content of the mix. There are many factors to be considered when choosing the most appropriate machine. Among these considerations are: » Affordability of end product

- » Type and scale of building structures
- » Availability of construction skills
- » Availability of maintenance possibilities
- » Reliability and cost of electricity

The manual machine is the most affordable option for block making and also the most convenient in rural settings due to the fact that it is manually operated and easy to use.

Technical specifications of the manual ISSB machine used in East Africa:

- » Typical compression force: 80-100N » Weight: 140kg
- » 2-4 workers in an 8hr work day can produce 400-600 blocks
- » Low maintenance: requires to be lubricated with engine oil.
- » 130 stabilised blocks can be produced from a 50kg bag of cement.

2.2.2. Process Analysis for Cement-Stabilised Blocks

- i. Planning the production of ISSBs starts with the site and the properties of the soil there.
- ii. Initially sedimentation test is conducted in the soil. A bottle is filled with 1/4 soil and 3/4 water and it is shaken and left for sedimentation. Wait 30 minutes for the soil to settle. The heaviest particles, gravels, will settle at the bottom followed by sands, silts, and clay at the top. This will give you an idea of proportions of each particles in the soil.
- iii. Shrinkage test is also conducted to the soil. Make or buy a wooden box with the dimension stated above and grease the interior. Fill the greased box with the sieved and moist soil to be tested. Compact the soil hardily into the mold. Leave the mold to dry for a week in a shaded area. After the soil has dried, note the shrinkage and record. When compared to the full length of the mold this ratio will inform the amount of stabilizer to be introduced into the mix.
- iv. Sending the soil sample to a laboratory to run tests is another option for testing soil suitability
- v. Suitable stabilizer is selected. The stabilizer can be of the following types:

- a. CEMENT OR LIME: Cement is the most common stabilizer used, however it is not recommended for soils with a high clay or salt content. On the other hand, lime serves very well for high clay content soils.
 - b. FIBROUS: Stabilization can be achieved through the introduction of a fibrous reinforcer into the soil mix such as dried grasses, animal hairs, or synthetic fibers.
 - c. CHEMICALS & RESINS: At present there are many chemical stabilizers being produced specifically for compressed earth block. There are natural resins and glues that can also be used for stabilization purposes.
 - d. SANDS AND GRAVEL: Sands and gravels can be introduced into soils with too much clay content in order to increase its density.
-
- vi. TRAINING OF LABOR FORCE - The making of ISSBs is a process based activity; the steps leading to good soil blocks must all be carefully performed to ensure quality. Training normally takes one to two weeks.
 - vii. EXCAVATION - Murram soil is recommended for the making of cement-stabilized blocks. This type of soil is found at sub-levels. Therefore, one must first remove the top soil to reach it.
 - viii. SIEVING - The sieving process is important in order to achieve good compact and smooth finish. To maximize effectiveness allow sieved soil to dry.
 - ix. MIX PREPARATION - Once the cement-soil ratio is determined by using the shrinkage test, mixing can start. This ratio is measured by the number of wheel-barrows against one bag of cement.
 - x. MIXING - Upon mixing the dry matter, introduce water for wet-mixing. This will activate cement and instigate reaction.
 - xi. MEASURING THE MIX - Depending on the soil mix, there will be an optimum quantity of it to be introduced into the machine mold to ensure facility of compression and maximum density.
 - xii. COMPRESSING THE MIX - Machine contains a stop which demarks full compression.
 - xiii. REMOVING THE BLOCK - When removing the block, check its texture and quality. If unsatisfied, throw back into the mix.

- xiv. DRY AND STACK - Stack blocks in layers of five and cover with grass or polythene paper. Full curing takes 28 days but blocks can be used before.
- xv. QUALITY CHECK - Introduce a fully cured block into a bucket of water for a day to observe its integrity and reaction.

2.2.3. Production of Thailand Interlocking Stabilized Soil Block (ISSB)

The building blocks were produced on the location of TISTR, also called Technopolis. The raw material composition for making the interlocking blocks are sand, laterite (containing sand/silt and clay) and cement. These are mixed together and then pressed to make building blocks using both hand press and machine press (Bredenoord, J., al et, 2019).



A) Raw materials mixed in mix machine



B. Block made from hand press



C. Block to be used for load bearing wall made from machine press

***Fig 2.31 Production of Thailand Interlocking Stabilized Soil Block (ISSB)
(Bredenoord, J., al et, 2019)***

2.3. SUSTAINABILITY PRINCIPLES OF INTERLOCKING EARTH BLOCKS

2.3.1. Low Embodied Energy

As per the author Bansal Deepak, Dy General Manager (Projects), HUDCO, Hudco Bhawan, Delhi, on his paper for the 15th International Brick and Block Masonry Conference, Florianópolis, Brazil – 2012, has stated that the Embodied energy Values (EEV) of hydraform interlocking blocks is much less compared to burnt clay bricks, as minimum cement and electrical energy are used to produce these blocks.

***Table 2.21 EEV for SEB Interlocking Blocks
(Deepak, B., 2012)***

EEV break up for SEB Interlocking blocks using Hydraform technology			
Raw Material	% age	Weight (kN)	EEV (MJ)
Soil	62.00%	190.96	0
C. Sand/ St. Dust	30.00%	92.40	0
Cement	8.00%	24.64	16509
Total	100.00%	308.00	16509
Power : 18.5 kw x 8 hr x 3.6 MJ			539
Total EEV per day production			17048
EEV per Hydra form Block (SEB) (size: 230 x 220 x 115)			6.09

**Table 2.22 EEV for Flyash Interlocking Blocks
(Deepak, B., 2012)**

EEV break up for fly ash interlocking block using Hydra form technology

Raw Material	% age	Weight (kN)	EEV (MJ)
Fly Ash	65.00%	172.90	0.00
C. Sand/ St. Dust	27.00%	71.82	0.00
Cement	8.00%	21.28	14258
Total	100.00%	266.00	14258
Power : 18.5 kw x 8 hr x 3.6 MJ			539
Total EEV per day production			14796
EEV per Hydra form Block (fly ash) (size: 230 x 220 x 115)			5.28

In the above tables 2.21 & 2.22, the EEV of water, soil, coarse sand and stone dust has been taken as zero as they are natural product and mining/quarrying is not considered due to various conflicting data based on different process involved. The transportation energy of all these materials has also not considered as this will be site specific.

**Table 2.23 Comparative Chart for EEV & Compressive Strength of Building Materials
(Deepak, B., 2012)**

Building Material	Size (cm)	Comp. Strength (N/mm ²)	Weight (N)	Density (kN/m ³)	EEV(Block) MJ	EEV (MJ/N)
Brick (conventional)	22.9x11.4x7.6	± 7.5	27.5	13.86	4.5	0.164
Hollow concrete block	40x20x20	± 4.0	268.8	16.80	11	0.041
AAC/CLC	40x20x20	± 4.0	192	12.00	11.5	0.060
Solid Concrete Block	30x20x15	± 7.5	216	24.00	10.4	0.048
HF (fly ash block)	23x22x11.5	± 7.0	95	16.33	5.3	0.056
HF (soil-cement block)	23x22x11.5	± 5.0	110	18.90	6.1	0.055
FalG Block	30*20*15	± 7.5	180	20.00	7.9	0.044

* MJ – Mega Joule

This is evident, that EEV of masonry with Hollow Cement concrete blocks, is least among all with a saving of about 70% EEV compared with burnt clay brick masonry, and HF(Hydra Form) fly ash block masonry is 65% less and HF(Hydra Form) soil block is 60% less than

the conventional burnt clay brick Masonry respectively. This masonry is structurally sound and environmentally viable.

2.3.2. Green Rating System - Credit Compliance

Interlocking mortarless masonry may help contribute to a building's LEED status over and above the use of mortar-jointed masonry through two different ways. LEED has potential credit opportunities for "Innovation in Design;" if successful in achieving this, interlocking masonry would gain one additional credit. The intent of the credit is defined as (USGBC, 2005).

"Provide design teams and projects the opportunity to be awarded points for exceptional performance above the requirements set by the LEED Green Building Rating System and/or innovative performance in Green Building categories not specifically addressed by the LEED Green Building Rating System."

For the specific innovative application of mortarless masonry, this credit may be awarded based on varying interpretations of its contribution to sustainable design. Construction processes often have an environmental impact through increased pollution: the use of vehicles, equipment, and possibly heaters can add up to a significant amount depending on the project. By greatly increasing the efficiency of the construction, the amount of pollution can be kept to a minimum.

Another interpretation could be that the overall amount of material used on the project has decreased. Mortar is usually a composition of Portland cement, water and sand. Portland cement production creates emissions that have proven to be harmful to the environment. By not requiring any mortar at all, the project has decreased pollution. For either interpretation, the larger the project is, the more significant the impact is on sustainability.

2.4. DESIGN FOR DECONSTRUCTION

The Design for Deconstruction is one of the principles of circular economy. The circular economy is a concept in which the industrial and consumption sector moves from linear economy in which the product is manufactured from raw materials, distributed, consumed and then disposed as waste. This waste generation cause harm to the ecology and put pressure on the natural habitat.

The UK Green Building Council point out that economy as whole can benefit from adapting circular economy concept. It is noted that transition to circular economy would mean

relevant actions from the stakeholders related to built environment. Real estate developers could be: 1) developing resource efficient products that are easy to repair and disassemble; 2) using delivery and return logistics to recover materials; 3) responsibly sourcing raw materials; 4) designing to minimise waste in product refurbishment and maximise re-use potential; 5) moving to alternative business models, for example, product service systems. Stakeholders linked to design and construction could be: 1) designing out waste; 2) designing for resource efficiency; 3) designing for deconstruction and disassembly; 4) using more renewable energy; 5) reducing carbon footprint over a whole building lifecycle (UK Green Building Council, 2017).

Construction activities create a living environment for a significant part of future generations. Circular construction must ensure that negative impacts on ecosystems are minimized. The impacts of negative built environment practices can contribute to increased air, water and soil pollution. They can have a destabilizing effect on the most significant levels of ecosystems, which can result in a reduction of biomass and influence the food chain, thus contributing to the loss of biodiversity.

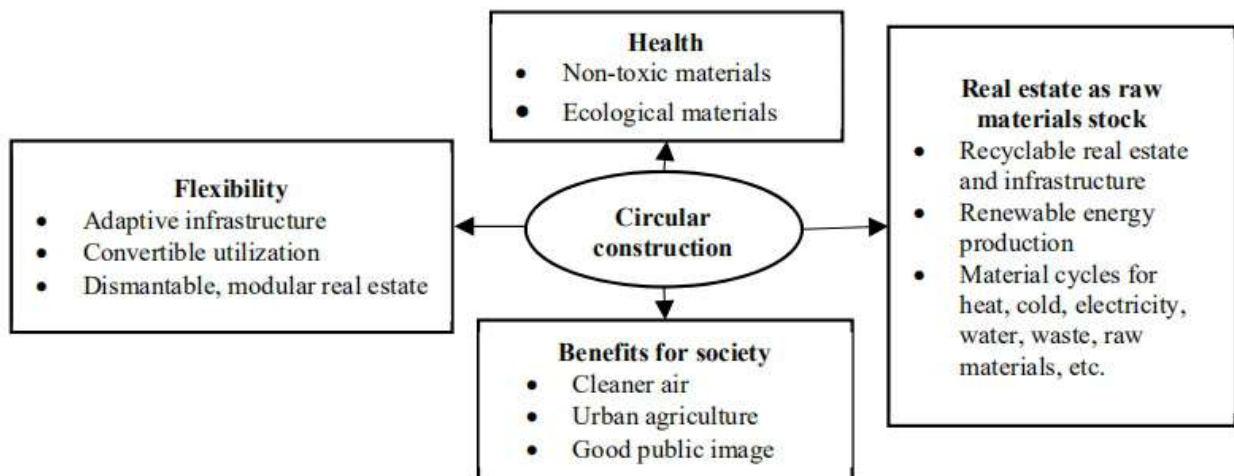


Fig 2.32 Circular Construction Implementation
(Zvirgzdins, J., Plotka, K., Geipele, S. 2019)

From the Fig 2.32, it can be seen that the flexibility is one of the main concept of circular construction. The flexibility in construction can be achieved through adaptive infrastructures which can change as per the user requirements and it can be converted as per the utilization. The building must be able to dismantle and deconstruct so that it can be alter as per the changing usage. This can be made possible only if the building is designed from the preliminary design stage with the concept of deconstruction in mind. The building that was already been design for deconstruction and has been constructed as per the proposed plan

can result in a sustainable building which shall have no negative impact to the environment when it reaches its end of life as the members of the structure can be removed and dismantled as per the pre-planned process so that the materials can be reused readily for other projects. A building must be dismantled instead of demolished for it produce zero wastage.

DfD is defined as “the design of buildings to facilitate future change and the eventual dismantlement (in part or whole) for recovery of systems, components and materials. This design process includes developing the assemblies, components, materials, construction techniques, and information and management systems to accomplish this goal”

2.4.1. Flexible Architecture

Flexible architecture was started during the start of Modernism. It started by the application of open floor plan design into the architecture. In 1914 Le Corbusier proposed a constructional system, named “Dom-ino”. It was a two-story unit, made up of concrete slabs supported on columns and a staircase. The developed prototypes were structural modules, ready frames, which only needed walls and windows. This system enabled architects to shape the elevation and the interior of the building regardless of the construction system (Magdziak, M., 2019, February). This started the concept of flexible construction.

“Flexible housing can be defined as housing that is designed for choice at the design stage, both in terms of social use and construction, or designed for change over its lifetime” (Schneider, T., & Till, J., 2005). The best-known constructional principle to facilitate flexibility in housing is that the ‘support’ or base building is differentiated from ‘infill’ or interior fit-out in residential construction and design. A support structure, as both technical device and social frame, ‘allows the provision of dwellings which can be built, altered and taken down, independently of the others’. The interior walls can be altered and moved easily if they are separated from the structural system and changes as per the changing needs through the time and users.

2.4.1.1 Adaptable Housing - Adjustment for Age, Disability and Family Life Cycle

Today's ideas of flexible space have their foundations in the modernists' thoughts on universal housing design. Flexible housing space has the ability to adapt to diverse users, but it also changes over time with the age of the inhabitants and the life cycle of the family. In the case of a single-family house, it is always possible to expand the building's volume and add additional space. However, looking for a flexible, fast and cheap way to enlarge the

space or its division in multi-family buildings is much more difficult (Magdziak, M., 2019, February).

An example of the flexible housing is house at Greenwich Millennium Village Phase II, London, UK. The architect is Proctor & Matthews and the project was designed in 2001. Identical plan forms of around 70m² can potentially accommodate a family, a couple that also uses the flat as a work space, and three independent people sharing. The subdivision is possible through acoustically sound sliding walls (Schneider, T., & Till, J., 2005).

From the fig 2.xx given below, it can be understood that the house can grow in its design as the building grows. The house initially was suitable for a couple with added work space. Later as the time goes, an additional wall can be added such that the house is suitable for a couple with kids. As further time passes, one more wall can be added such the the house can accommodate three adults in the house.



Fig 2.33 Flexible Housing - London
(Schneider, T., & Till, J., 2005)

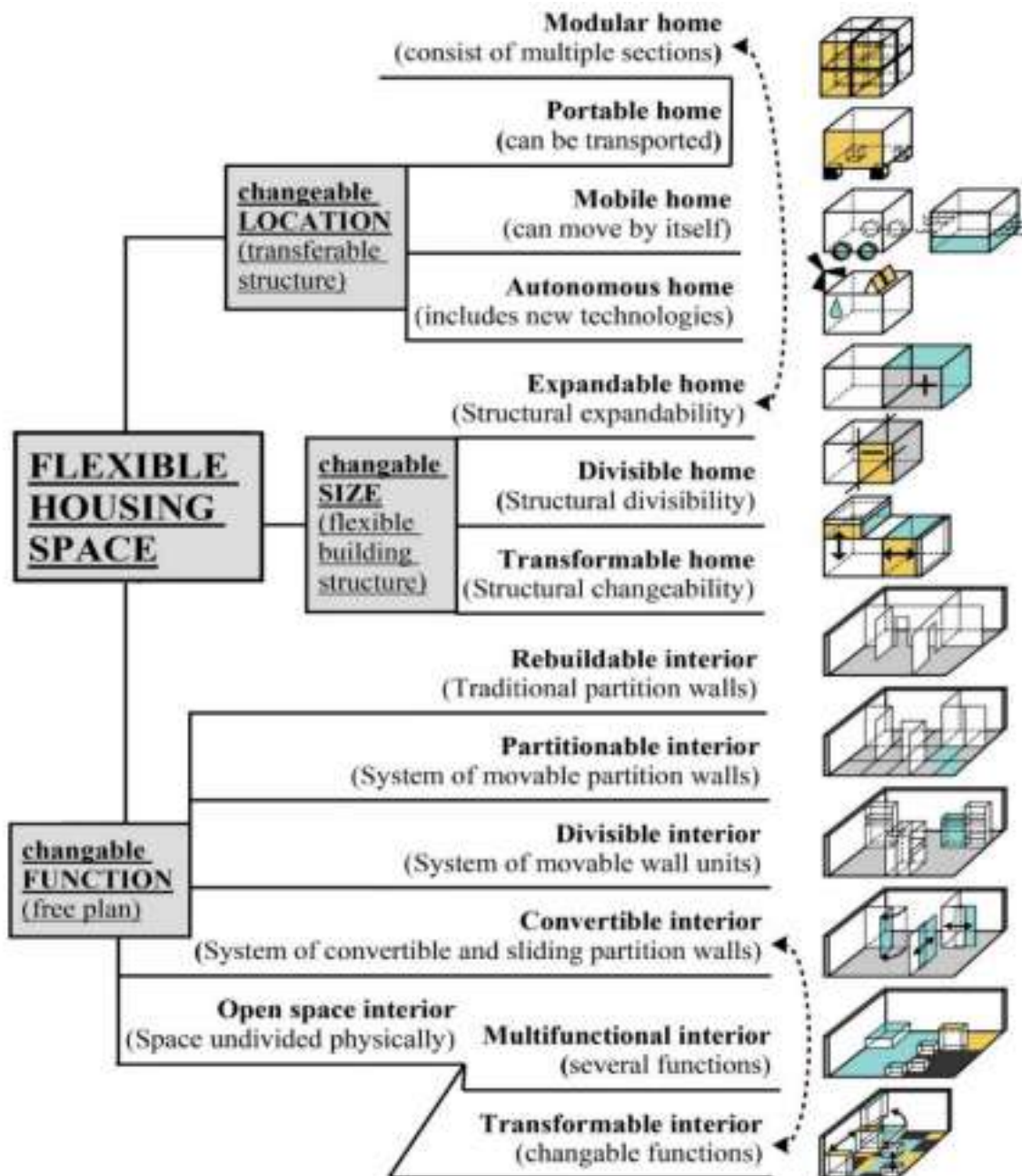


Fig 2.34 Circular Construction Implementation
(Magdziak, M., 2019, February).

2.4.2. Design for Deconstruction Priorities

The key principles of DfD are listed as follows:

- Simplify and modulate the structure and the form. Use an easily reusable, standardized structural grid that also allows for parallel deconstruction through independent support structures. Also design foundations to allow for vertical expansion instead of demolition.
- Document the materials used and the proposed methods of disassembly for those materials. [Information technology should be used to record an informative database of materials used in construction. This database should be referenced in the event of maintenance, renovation, or total deconstruction of the building. Materials should be easy to identify and methods should be illustrated for universal understanding.
- Select materials with consideration of future impacts in terms of value, durability, recyclability, interchangeability, and simplicity of separation.
- Design simple, accessible connections with no chemicals. Simplifying connections minimizes the variety of tools needed for disassembly and the time spent switching from one tool to the next. Connections must be well exposed to ease their separation. Chemical adhesives contaminate materials making them unusable for recycling or reuse.
- Separate MEP systems. As stated before, even for the sake of maintenance and renovation, these systems can create a labyrinthine web of confusion for workers to navigate.
- Use lightweight materials that match the human laborers responsible for disassembly.
- Provide full specifications and warranties and describe the design life and/or service life of materials and components.

Table 2.24 Ten Principles of DfD

Design and Detailing for Deconstruction - SEDA Design Guides for Scotland: No. 1	
Sl. No.	Principles
1.	Document materials and methods for deconstruction
2.	Select materials using the precautionary principle
3.	Design connections that are accessible - Avoid requirements of expensive equipments

4.	Minimize or eliminate chemical connections - Make easy separation & recycling
5.	Use bolted, screwed and nailed connections - Use standard & limited palettes of connectors
6.	Separate mechanical, electrical & plumbing (MEP) systems
7.	Design to the worker & labor of separation - ease of removal & decrease labor intensity
8.	Simplicity of structure and form for ease of construction and deconstruction
9.	Interchangeability - principles of modularity, independence, and standardization
10.	Safe deconstruction - reduce risk, allow safety of workers, equipment, site access

Source: (Morgan, C., & Stevenson, F., 2005)

Table 2.25 Roles and Responsibilities by Design Phase for DfD

Phase		Client	Designer	Contractor
1.	Pre-Design	1. Support scenario planning. 2. Hire an architect who is experienced in sustainable design and DfD. 3. Brief the design team on critical requirements for upgrading, adaptability and flexibility in use. 4. Stimulate 'As Build' drawings and specification as part of the design contract.	1. Conduct integrated scenario planning and programming. 2. Demonstrate best practice of DfD to client. 3. Investigate DfD relative to building type and client needs. 4. Develop goals and priorities for DfD including which building elements are most cost-effective to DfD.	-
2.	Concept Design	1. Engage contractor as expertise on design	1. Organize meetings with the contractor and major vendors to identify reused	1. Obtain initial briefing and training on DfD

		implications for DfD.	materials and construction processes which support DfD.	
3.	Schematic Design	-	1. Carry out a design check by producing an outline plan for the deconstruction of the building and ensuring that the design proposals are consistent with this form of reverse engineering.	2. Advise the design team on deconstruction processes, potential salvage and reuse priorities, and recycling requirements for various material types.
4.	Design Development	-	1. Produce a detailed plan for the deconstruction of the building.	1. Advise design team on implications for deconstruction in relation to design and detailing (where possible).
5.	Construction Documents	-	1. Insure details have been implemented to not compromise their DfD integrity. 2. Incorporate plan for deconstruction into drawings specifications. 3. Insure bid documents reflect commitment to DfD construction.	2. Advise the design team on implications for construction and deconstruction of design and detailing (where possible). 3. Identify good construction practice to promote DfD

				and advise design team accordingly. 4. Advise design team on 'plan for deconstruction' drawings and specifications
6.	Construction Administration	1. Ensure that all maintenance staff and contractors are fully briefed on DfD strategies. 2. Allow for additional time in contract period for construction to insure DfD through careful practices.	1. Create or update the construction documents to create comprehensive "as built" documents.	5. Insure quality of workmanship to maintain integrity of DfD details as designed. 6. Train sub-contractors as necessary.
7.	Facility Operation Services	1. Monitor the performance of project over time (where possible) and build in the evaluation into future DfD.	1. Insure that all maintenance staff and are fully briefed on DfD strategy, and instigate a 2. feedback strategy on building performance from DfD	-

Source: (Morgan, C., & Stevenson, F., 2005)

2.4.3. Design for Deconstruction Benefits

According to the SEDA Design Guide (Morgan, 2005), economic-related benefits of Deconstruction include the following:

- Increased flexible use and adaptation of property at minimal future cost
- Maximized value of a building's elements, when it is only required for a short time
- Reduced quantity of materials going to landfill, and thus tipping fees
- Reduced future liability to pay higher landfill taxes
- Reduced risk of financial penalties in the future, due to changing legislation, through easily replaceable building elements

Other environmental benefits are,

- avoiding the induction of virgin materials into the wastestream
- Cost benefits of selling salvaged materials as compared to demolition

The social benefits are,

- brings more jobs to low-skilled workers than demolition
- allows low-income communities access to high quality salvaged materials that would have been otherwise too expensive

2.4.4 Design for Deconstruction Plan

An important element of the DfD process is the documentation and dissemination of the building's design intent per its materials, components, connections and form.

A comprehensive Deconstruction Plan will insure that designed-to-be-reusable building elements will be recovered as intended. The Plan should be issued to all parties at the outset of the building contract to ensure a construction process that does not compromise the DfD and Deconstruction Plan. For a successful Deconstruction Plan, which is a part of the overall DfD detailed plan, make sure the following tasks are undertaken:

1. Statement of strategy for DfD relating to the building

Demonstrate the strategy behind the designed re-usable elements and describe best practice to ensure they are handled in a way which preserves maximum reusability.

2. List building elements

- Provide an inventory of all materials and components
- Describe the design life and/or service life of materials
- Identify best options for reuse, reclamation, recycling and waste to energy for all building elements.

3. Provide instructions on how to deconstruct elements

- Provide up-to-date plans for identifying information on how to deconstruct buildings.
- Where necessary add additional information to the “as built” set of drawings to demonstrate the optimum technique for removal of specific materials
- Describe the equipment required to dismantle the building, the sequential processes involved and the implications for health and safety as part of the management requirements.
- Ensure that the plan advises the future demolition contractor on the best means of categorizing, recording and storing dismantled elements.

4. Distribution of DfD Plan

- Revise the plan as necessary and reissue to all parties at the building completion stage, so that there is maximum awareness of the DfD requirements for the future, including building owner, architects and builder.

2.5. INDIAN CODES AND STANDARDS FOR INTERLOCKING BLOCKS

IS 2110: 1980	Code for practice for in situ construction of wall in building with soil cement.
IS 1725: 1982	Specification for soil-based blocks used in general building construction.
IS 4326: 1983	Earthquake resistant design and construction of building code of practice.
IS 1905: 1987	Code of practice for structural use of unreinforced masonry.
IS 5454: 1978	Method for sampling of clay building bricks
IS 4130: 1991	Demolition of buildings - Code of safety
IS 1200 (Part-III): 1976	Methods of measurement of buildings and civil engineering works - Brick works
IS 2212: 1991	Code of practice for brick works

2.6. LITERATURE CASE STUDY

2.6.1. FLEXLOCK HOUSE. MAGNOLIA, TEXAS: CASE STUDY 1

Building Type:	Residence
Designer:	CAD-FM Design Architecture Firm
Structural Engineering:	Ryan-Biggs Associates
Location:	Magnolia, Texas, US
Building Area:	2958 sqft
Building team:	Cercorp Initiatives Inc., Southwest Concrete Products, Williams Form Engineering D&H Masonry
Interlocking Block Model:	FlexLock system by Cercorp Initiatives Inc
Year of Completion:	2006
Construction Duration:	4 Days

The flexlock house was developed by Cercorp Initiatives Inc, a company providing innovation solutions to building industry. The Corcorp initiatives is building technology solutions providing company with its base in United States. They have developed a new interlocking system, FlexLock Wall System, to replace the conventional wall masonry system to provide efficient and sustainable alternative which reduces the cost and labour requirements.

The FlexLock Wall System, developed by Cercorp Initiatives, was chosen as the primary building material for a project in Magnolia, Texas in order to study the benefits of mortarless blocks. The scope of work for the project consisted of a 275 m² (2,958 ft²) house with construction starting in June 2006 (Cercorp Initiatives, 2010). The project consisted of all of the standard elements included within a typical masonry structure: lintels, jambs, sills, and bond beams. This provided a comprehensive comparison with conventional masonry units. Using about 213.7 square meters of FlexLock units, all perimeter walls, one interior bearing

wall, and the demising wall separating the garage from the interior living space were fully erected in approximately four days.



Fig 2.35 FlexLock House Project

2.6.1.1. FlexLock Wall System

FlexLock is a mortarless, groutless, post-tensioned masonry wall system designed to replace conventional masonry block construction. The FlexLock design team began with a simple concept, develop an innovative masonry building system for the 21st Century. Beyond the technical challenges, the new system would have to take into account industry-specific market demands shaped by a changing global economy.

The design specifications included: reduced costs, rapid on-site construction, the use of unskilled labor, superior seismic and wind performance, and all-season construction. Unlike conventional masonry, a FlexLock structure can be disassembled and most of the masonry and hardware can be used to build again

The advantages of FlexLock Construction are:

- i. **Mortarless** - Except for the first course, the FlexLock® system requires no mortar between the joints or grouting of the cores.
- ii. **Reduced Construction Time** - The FlexLock® Wall System can be assembled three to four times faster than conventional block construction.

- iii. **Work Force/Market Sensitive** - According to the World Center for Concrete Technology, the average age of a journeyman in the U.S. is 52 years old and estimates indicate a shortage of over 50,000 masons. Because FlexLock® requires one journeyman (the rest being stackers), it can accommodate this shortage by configuring itself to the current labor pool.
- iv. **Completely Reusable** Should the need ever arise, as in the case of interior partition walls, the unique interlocking surfaces allow for total disassembly rendering the components useful for other construction projects. This also allows for mistakes to be easily fixed.
- v. **All Season Construction** Conventional block walls require expensive additives to enable the mortar to cure in sub-zero temperatures. As a result, many colder climates do not build during the winter months. Because the FlexLock® Wall System uses very little mortar, it can be assembled in any temperature zone extending the working season.
- vi. **Super Strong Wall** - Structural tests conducted by the National Concrete Masonry Association demonstrate that FlexLock® has three to four times the reserve strength as standard masonry. This, along with the ability to flex, enables the system to dissipate loads while still maintaining its structural integrity. This feature is expected to make the FlexLock® Wall System applicable to seismic regions.
- vii. **Lower Overall Construction Costs** - The above advantages further translate into significant monetary savings.

2.6.1.2. FlexLock Wall System - System Components

The FlexLock® Wall System is comprised of two sub-systems; masonry and hardware. It is the unique combination of these, along with the diamond-ground mating surfaces of each block, that give the system its strength and structural integrity.

I. Masonry Sub-System

The stretcher, universal corner and bond units make up the masonry sub-system. Although other units such as half-stretchers and bullnose can be easily produced, the stretcher, corner and bond units are extremely versatile and will suffice for most projects. FlexLock® can also be produced as architectural units such as split face, ground and fluted.

Stretcher: The stretcher unit (Fig 2.37) is comprised of parallel shells with ground bearing surfaces. The thick main web at the front of the unit contains a vertical slot through which the tendon is placed. The unit has male and female interlocking mating surfaces on two of its six sides. To allow ease of assembly, these are deliberately kept loose and only engage when the wall is under a lateral load.

Corner: The universal corner unit (Fig 2.37) is comprised of a continuous shell on three of its four sides. Like the stretcher unit, the thick main web at the front of the unit contains a vertical slot through which the tendon is placed. Depending on its orientation, a single unit can be used for both inside and outside right angles. Beyond its use as a corner block, the universal corner unit is also used as a jamb block. This provides a smooth solid surface along openings to attach a window and door jamb.

Bond Unit: The bond unit (Fig 2.36), sometimes called a channel block, is a hollow concrete masonry unit with depressed sections forming a continuous channel in which reinforcing steel can be placed for embedment in grout. The bond unit is also available with a return to effect corners. Like the stretcher and corner, the bond beam is ground on both bearing surfaces.

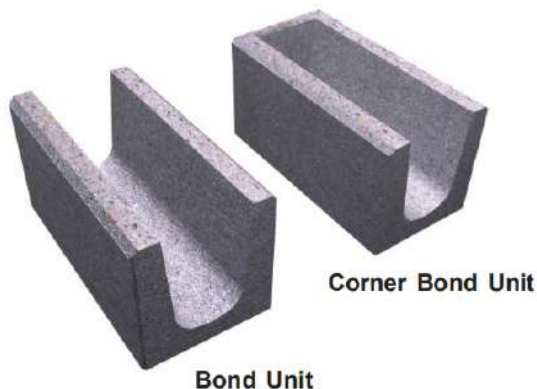


Fig 2.36 Bond Units

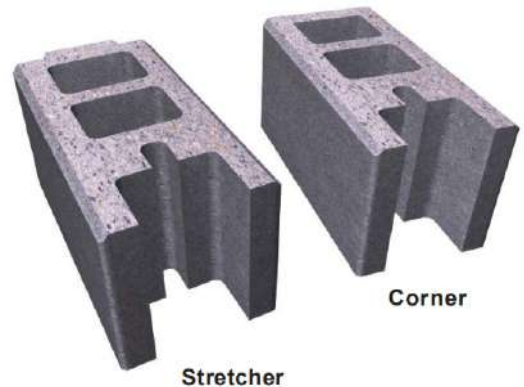


Fig 2.37 Stretcher & Corner Units

II. Hardware Sub-System

FlexLock® hardware is comprised of various steel components used to tie the system together and provide its strength.

Bearing Plate: The bearing plate (Fig 2.38) is a simple 5/8" mild steel rectangle measuring 7 7/8" x 4". The plate has one 7/8" hole in the middle to accommodate post-tensioning.



Fig 2.38 Bearing Plate

Tendons: The tendons (Fig 2.39) are comprised of #5 Grade 60 ASTM A615 all-thread-rebar designed and tested for compressing masonry units. The 5/8" nominal threads are cold rolled with a minimum ultimate strength of 28.8 Kips and a minimum yield strength of 19.2 Kips. The innovative all-thread design minimizes waste and allows for easy threading. Tendons are available in lengths of 5', 10', and 20'.

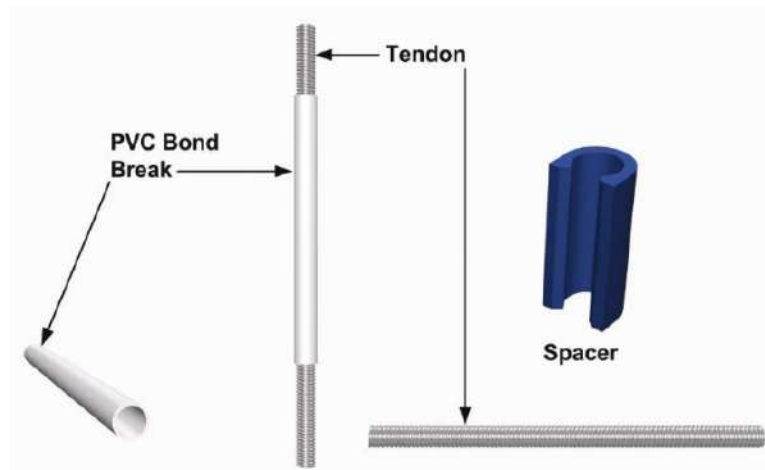


Fig 2.39 Tendon

Bond Break: A 3/4" class 200 (SDR21) nominal PVC tube is used to create a bond break (Fig 2.39) between the tendon and surrounding grout. This is used in a bond beam application and available in ten foot lengths.

Spacers: PVC spacers (Fig 2.39) are used to reduce the space between the masonry slot and the tendon. When forces are applied perpendicular to the wall (out-of-plane), the spacers provide a vertical interlock dispersing the load through the tendon. For

convenience, the spacers snap and lock around the tendon eliminating the need to thread them from the top.

Nuts, Washers and Couplings: Fasteners such as hex nuts, washers and couplings (Fig 2.40) are all designed to exceed 100% of the tendons ultimate strength. A special wing nut can be used, along with a universal bearing plate, to temporarily lock down a wall during construction. All components are machined to specific tolerances to yield a highly effective, yet durable, threaded connection.



Fig 2.40 Nuts, Washers and Couplings

Corrosion Protection: All tendons and fasteners are hot-dipped galvanized to ASTM A-153. Other forms of corrosion protection such as epoxy, mastic wrap, and heat shrink plastic tubing are available also.

Using Mortar and Grout with FlexLock® : As noted earlier, FlexLock® is a mortarless and groutless system. It is mortarless in the sense that mortar is not used between the head and bed joints. It is groutless in the sense that grout is not used to fill the vertical cores. Since these are the two principal ways in which grout and mortar are used in masonry, FlexLock® is considered both virtually mortar-less and virtually groutless. However, the system is not completely mortarless and groutless. Mortar is used between the footing and first course. Grout is used in the jamb, sills, lintels, and bond beam. Grout and mortar can also be used to mate FlexLock® additions to conventional masonry, and in special situations. In many respects, FlexLock® is really a hybrid between post-tensioning and conventional masonry, exploiting the structural capabilities of both, and allowing the experienced mason to make an easy transition.

2.6.1.3. FlexLock House Construction Process

Stage-1: Pouring the base slab



Stage-2: The Finished Slab



Stage-3: Dry Laying the First Course



Stage-4: Drilling the Anchor Holes



Stage-5: Grouting the Anchors



Stage-6: Pre-Stressing the Anchors



Stage-7: Laying the First Two Courses



Stage-8: Dry-Stacking the Walls



Stage-9: Setting the Lintels



Stage-10: Sills and Jambs



Stage-11: Gouting the Bond Beam



Stage-12: Tensioning the Walls



Stage-13: Finished Interior



Stage-14: Finished Exterior



Fig 2.41 Construction Process of FlexLock House

2.6.1.4. FlexLock House - Cost Savings

At the time of construction, the Magnolia region had an average installed price of roughly \$75 per m² for conventional masonry units. After breaking down the cost of the FlexLock System project, the price came to \$57.24 per m² (Cercorp Initiatives, 2010). This is a reduction of 24% in 17 installed cost. The Flexlock construction is able to achieve cost saving through Use of unskilled labor, Rapid construction, Eliminates mortar between units, Eliminates grouting the cores, All-Season construction

2.6.1.5. FlexLock House - Labour Efficiency

The labour crews were inexperienced with the mortarless product, yet were still capable of stacking blocks at an average rate of 164 blocks an hour. When compared to conventional masonry, this is an increase in productivity of over 100%. While FlexLock still requires a mason to lay the first course, the other courses are dry-stacked using unskilled labor. This means that masonry contractors can re-configure their labor force so that a team consisting of three masons can now consist of one mason and two unskilled stackers. Reduced labor costs and increased productivity drive the in-wall costs down.

2.6.1.6. Cost Comparative Analysis

The cost analysis is carried out between the conventional masonry system and FlexLock system. Both FlexLock and conventional masonry utilize common methods of pouring a footer, inserting reinforced steel dowels (in the case of FlexLock threaded anchors), and grouting the bond beam. The main differences were a reduction in the need of mortar, labor

time, and skill level. Both FlexLock and standard CMU construction require the same labor and materials for the footer and bond beam. The two systems diverge based on the specific items noted below.

The following descriptive estimate is based on:

- a. Interviews with three journeymen masons
- b. Consultation with the International Masonry Institute
- c. Consultation with the National Concrete Masonry Association
- d. Consultation with the Masonry Contractors Association of America
- e. Discussion with an estimator from J.D. Long Masonry
- f. Discussion with an estimator from D&H Masonry
- g. Instructional material from: A Mason's Guide to the FlexLock Wall System

A. Relevant Factors in Standard CMU Construction

The structure requires 2,564 eight inch masonry units. This equates to an actual combined wall area (minus window and door openings) of 2,282 square feet. According to Ryan Knight, estimator for D&H Masonry, the average square foot installed cost for eight inch gray block residential construction in the Houston area is \$7.00. This would place the total masonry cost for the structure at \$15,974. Since this \$7.00 per square foot installed is well established and is a composite of all the relevant factors (materials, labor, and miscellaneous) in masonry construction, it will be used as a benchmark upon which the FlexLock system will be compared.

B. Relevant Factors in FlexLock Technology

Running the same number of courses and assuming, the same openings. The cost reductions came from the reduced need for mortar material and labor (mixing, application, etc.). Additional savings come as a result of the reduced expertise required to build the structure, as well as the more rapid construction speed. While block size is virtually the same for both systems, FlexLock units retail for \$1.50 (due to its unique features requiring special molds and manufacturing processes) for a total cost of \$3846.

C. Establishing Productivity Rate For FlexLock

Prior to the build, a study was performed and, based on established industrial engineering methods, a productivity rate was developed. This rate is based on Normal Time which is the average observed performance time to stack a single FlexLock unit taking into account the performance rating of the stacker. Normal Time is not directly used for establishing labor

costs, but acts as a a time-study reference point necessary to determine accurate labor costs. The formula for Normal Time is as follows:

$$NT = (CT) \times (PR)$$

NT = Normal Time

CT = Cycle Time (the time it takes to stack one unit)

PR = Performance Rating (quality of the performance based on skill and experience expressed in a percent with 100% being an average worker)

Table 2.26 Cycle time of laying Interlocking Blocks

No	Task	Description	Time (Sec)	Assumption and Comments
1.	Fetch	Retrieve unit from cube	4	The unit is placed within 10' proximity to the labour
2.	Lift	Pick up unit	2	Using established OSHA Standards
3.	Return	Go back to the wall	4	The unit is placed within 10' proximity to the labour
4.	Inspect	Look over block	2	Examine for imperfection
5.	Check	Check surface for debris	3	Quick visual look at bed joint
6.	Clean	Remove debris	1	This is rarely the case
7.	Lay	Place block on the wall	2	Ensure proper orientation
8.	Seat	Rock to secure	2	Reducing the possibility of point loading
Per cycle time in seconds			20	

Normal Time: To establish the Normal Time for FlexLock, the per unit cycle was broken down into specific tasks and each of these were observed in a realistic work situation. The following times are taken from time studies conducted at the International Masonry Institute in April and June of 2003. The control structure was three wall panels and a small FlexLock structure with window and door openings

$$NT = (CT) \times (PR)$$

$$20 = 20 \times 1$$

Standard Time: Normal Time provides a basis for determining the actual "real world" time it takes to stack FlexLock. This "real world" time is called Standard Time, which is an industry benchmark used to accurately determine labor costs. Simply put, Standard Time is Normal Time adjusted for any planned non-productive time known as Allowances. Allowances are work delays that include: bathroom visits, drink, physical or mental strain, tediousness, as well as heat and humidity. Other unplanned work stoppages such as late shipments or rain delays are not calculated in labor costs. An Allowance Factor of 7% to 9% is considered an industry standard.

$$ST = NT (1+A) \quad ST = \text{Standard Time}$$

$$NT = \text{Normal Time}$$

$$A = \text{Allowances (expressed in a percent)}$$

$$ST = NT (1+A)$$

$$22 = 20 (1+ 0.10)$$

Based on Standard Time, it takes 22 second to stack one FlexLock Unit. This equates to 164 block an hour. However, given normal physical constraints of a construction worksite, it is more reasonable to hold a production rate of 120 units an hour or the stacking of one unit every 30 second. Keep in mind that each of the stackers are supported by one laborer whose only task is to place block no less than ten feet from any point. Since there is no real difference between a stacker and laborer, they can trade-off if fatigue sets in. Because this was the first FlexLock structure, and because the crew was not FlexLock certified, the lack of experience in material handling and training resulted in considerable time loss. As a result, the labor productivity rates for this first project were reduced significantly. Still, this is substantially faster than standard masonry by over 100%. Moreover, the stackers (which were comprised of day laborers) represented a substantial reduction in labor costs. Both profit and productivity will increase as greater efficiency is gained.

D. Comparative Analysis Conclusion

Relevant Effect of FlexLock Technology: Based on a comparative cost analysis of the structure, and using the installed cost of standard 8" masonry in the region, the total masonry costs for the FlexLock structure decline by 24% and productivity increased by two-fold. This analysis incorporates fair market value of the resources for the specified project.

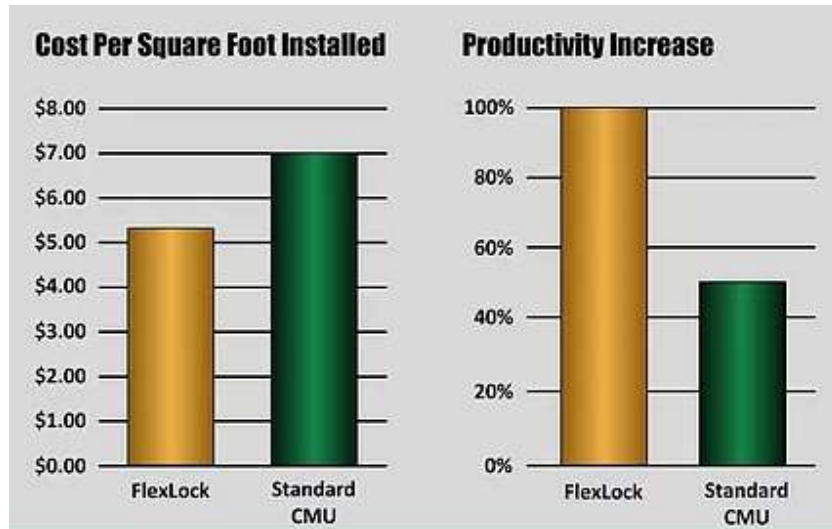


Fig 2.42 Comparative Analysis - Conventional vs FlexLock

Post-construction, a cost study was performed by Cercorp Initiatives, the developer of the FlexLock system, to compare the cost of using the FlexLock system with conventional masonry construction. Working with a mason contractor, the study estimated that the cost of using FlexLock was approximately 25 percent less than conventional means, along with an increase in productivity of nearly 120 percent. The savings were generated through reductions in mortar and grout materials, time and labor to prepare and place those materials, and time required for installation. The need for fewer skilled masons was also a contributing factor.

2.6.1.7. Workings of FlexLock System

In conventional building system, the load is carried through horizontal and vertical reinforced columns, beams, slab, lintel, etc. However, the FlexLock system carried the load to post-tensioning. The Post-tensioning is a method of strengthening masonry or other materials with high-strength steel bars known as tendons. It is known fact that the concrete is great in taking compressive load. But, concrete is weak in carrying compressive load. Hence, the interlocking concrete blocks can take compressive loads but to carry the tensile load, reinforcement in the form of tendons is used.



Fig 2.43 First course set in mortar around vertical tendons.

Typically, steel reinforcing bars are grouted in the block cores as tensile reinforcement to limit structural failure. This method is known as passive reinforcement because it does not carry any of the applied load until the wall deflects. On the other hand, post-tensioning provides a form of active reinforcement. Because it is pre-stressed prior to any load, the tendon is effective as a reinforcing element prior to any deflection.

In the FlexLock® Wall System, the precision units are held in compression, from top to bottom, with high strength steel tendons. While the bottom of the tendon is typically anchored into the footing, the top of the tendon is secured through a steel bearing plate on top of a bond beam. There, a hex nut and flat washer are used in conjunction with a small hydraulic jack or torque wrench to tension the tendon and compress the masonry. With a bond beam grouted solid at the top of the wall, and the tendons firmly fixed into the footing, a solid crown is formed at the top and bottom. This sandwiches the entire structure under compressive force giving it considerable strength (Fig 2.44)



Fig 2.44 Structural System of FlexLock

In mortared systems that use post-tensioning, the tendon is placed through the center of the hollow cores. In the FlexLock® system, the tendon is contained in a specially designed slot. The slot places the tendon in a restricted space enabling the tendon, with the spacer, to engage the masonry units when the wall is deflected. This engagement allows the wall to further resist the force by pressing against the already stressed tendon. The orientation of the stretcher units are alternated at each course allowing for a 360 degree containment of the tendon (Fig 2.45). When catastrophic forces are applied to a FlexLock® wall, the wall begins to deflect without losing its structural integrity (Fig 2.46).

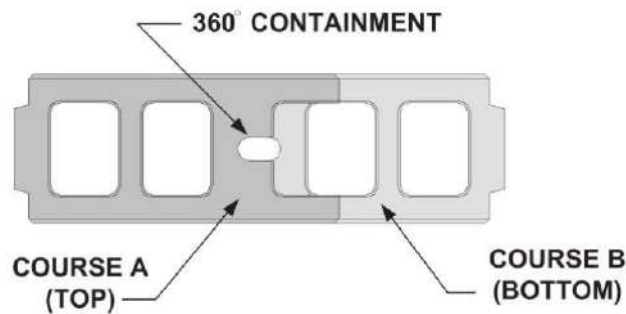


Fig 2.45 Alternative Courses with Tendon Cavity

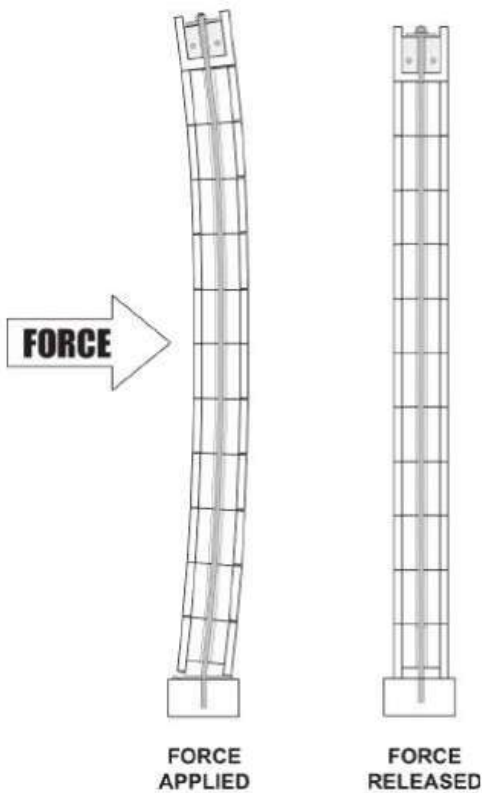


Fig 2.46 Wall Structural Movement



Fig 2.47 Laying of First Course

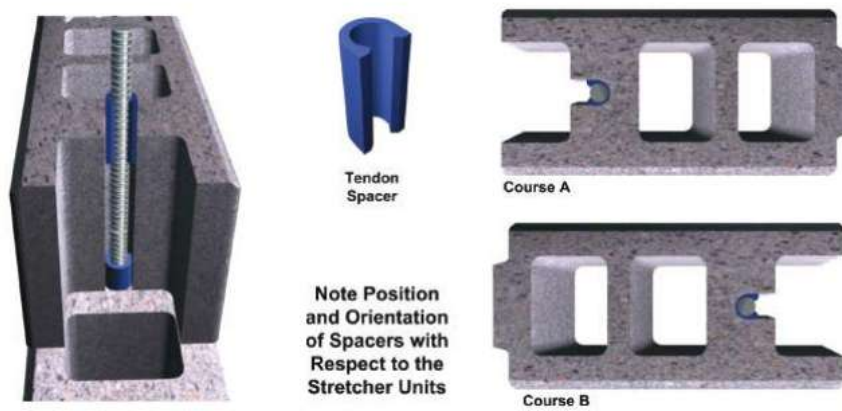


Fig 2.48 Tendon with Spacer

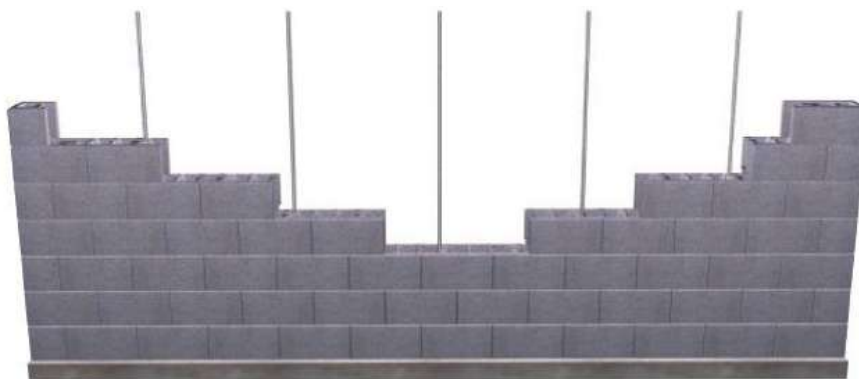


Fig 2.49 Tendon Configuration

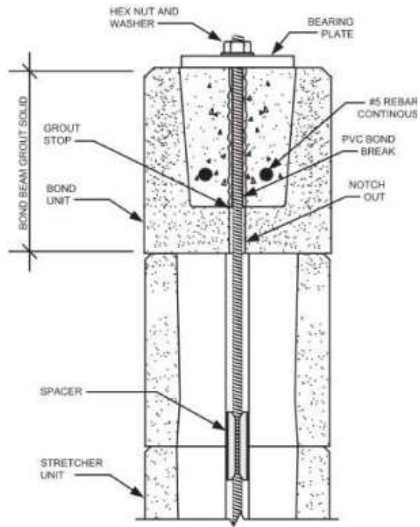


Fig 2.50 Capping Details (OP-1)

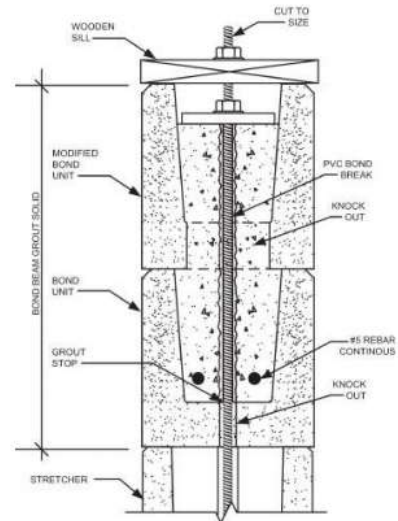


Fig 2.51 Capping Details (OP-2)

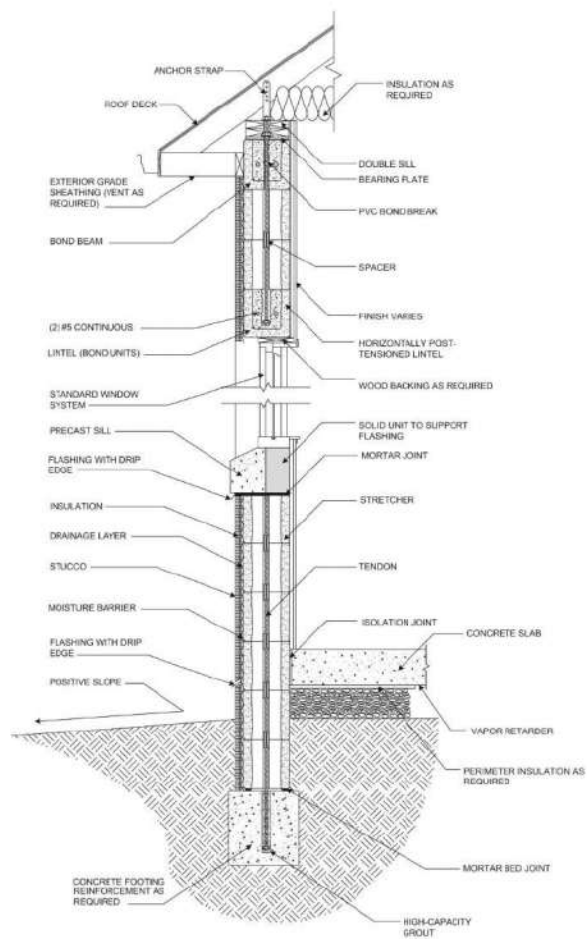
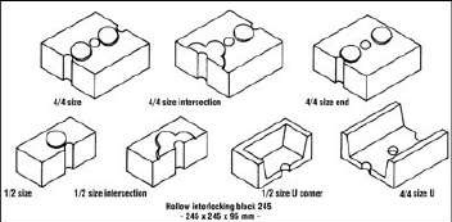
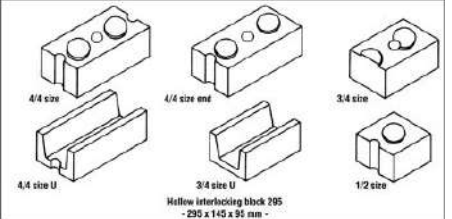
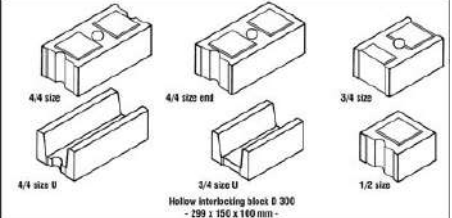


Fig 2.52 Wall Section Detail

2.6.2. DISASTER RESISTANT HOUSES BUILT BY THE AUROVILLE EARTH INSTITUTE: CASE STUDY 2

Since the year 1995, the Auroville Earth Institute has worked towards the development of reinforced masonry with compressed earth blocks. The institute has developed three types of blocks - Square hollow interlocking block 245, rectangular hollow interlocking block 295 and rectangular dry hollow interlocking block 300. These blocks were used to construct the disaster resistant homes in India and in other countries. The homes were developed for disasters such as earth-quack and tsunami.

Table 2.27 Types of Auram Hollow Interlocking Blocks By Auroville

Sl. No	Block	Image	Properties
1.	Square hollow interlocking block 245		allows building up to 2–3 floors high. It is laid with mortar and a grout is cast into the holes.
2.	Rectangular hollow interlocking block 295		used only for ground floors. It is laid with mortar and a grout is cast into the holes.
3.	Rectangular dry hollow interlocking block 300		used only for ground floors. It is laid dry stacked and a grout is poured later on into the holes.

First Prototype:

The first prototype of an earthquake resistant house was built at Istanbul, Turkey in 1996. It was sponsored by UNCHS/HABITAT. It was pre-cast in 10 days using semi-skilled labour and it was assembled in 8 days during the “1996 City Summit / HABITAT” at Istanbul – Turkey. It was done at the request of CRATerre and the United Nations. The area of the demonstration house is 9 sqm.



Fig 2.53 Minimum Emergency House, Istanbul, Turkey - 1996

Second Prototype:

In 1999, at the request of the Housing and Urban Development Corporation (HUDCO), the Auroville Earth Institute built another demonstration house of 23 sqm - The AUM House, in New Delhi during the “All India International Trade Fair”. This house was precast in 3 weeks in Auroville and then transported to New Delhi via lorry over 2900 Km in 5 days with carrying load of 22.5 ton. The structure was assembled in New Delhi in 66 hours by a team of 18 men. It was granted a gold medal by ITPO for the quality of the special demonstration. This house was an earthquake resistant house and it was building with all facilities like water, sanitation, kitchenette and smokeless stove.



Fig 2.54 AUM House, New Delhi, India - 1999

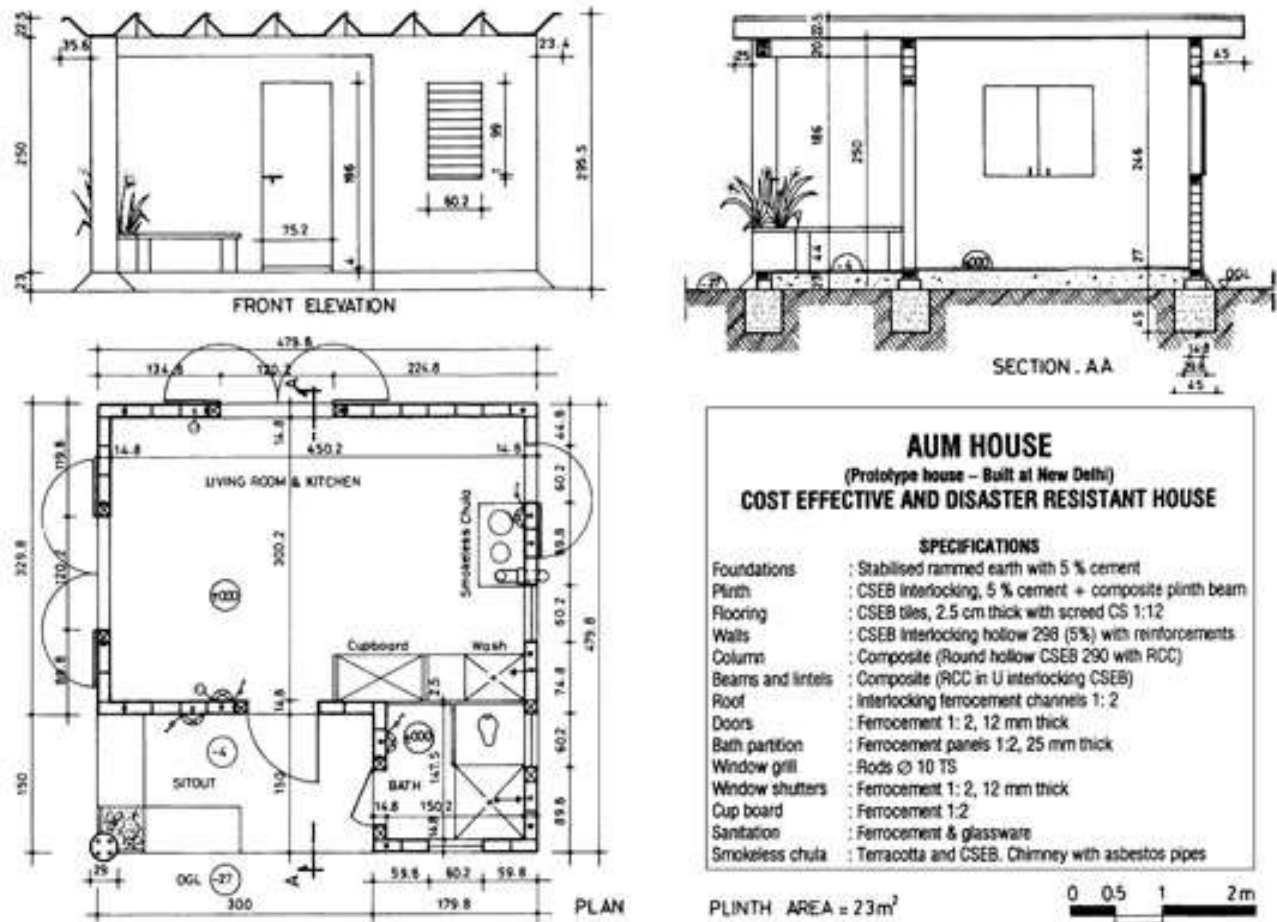


Fig 2.55 Plan of AUM House, New Delhi, India - 1999

Third Prototype:

Another demonstration was started for the rehabilitation programme in the zone affected by the severe earthquake which struck the district of Kutch in 2001. The AUM house was precast in Auroville and assembled in Gujarat, India, in 62 hours by a team of 20 men. Since then, this technology has been developed and transferred to the Catholic Relief Service (CRS), an NGO that implemented it for large scale rehabilitation of Kutch district. The CRS designed various types of houses of 28sqm and 4000 houses are being built in a year by local team. This prototype model was simplified from the previous prototype and was built without sanitation. But, it has also been improved and reinforced. This technology has been approved by the government of Gujarat as a suitable method of construction for the rehabilitation of the zones affected by the 2001 earthquake.



Fig 2.56 AUM House, Gujarat, India - 2001

Construction Process of AUM House, Gujarat:



6 hours – Digging the foundations



11 hours – Stabilised Rammed earth foundation completed



13 hours – Building the first course of the plinth



14 hours – Building the second course of the plinth



16 hours – Plinth beam completed



17 hours – Filling the basement and starting the walls

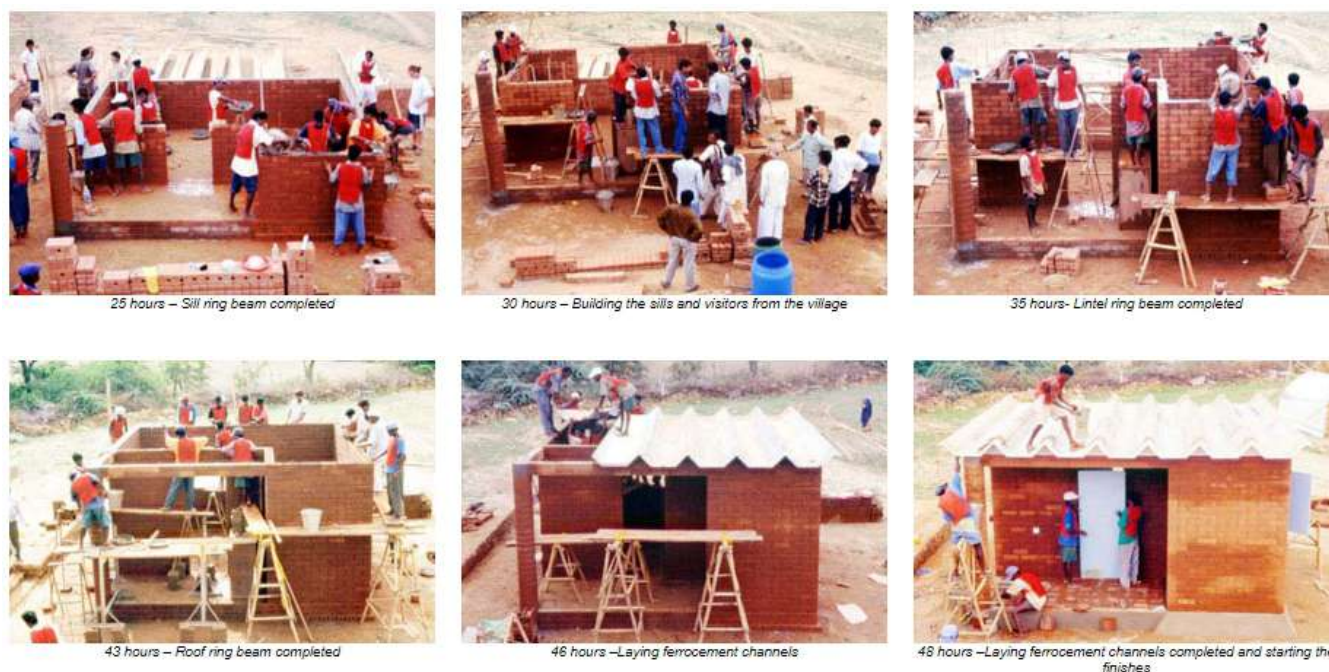


Fig 2.57 AUM House Construction Process, Gujarat, India - 2001

Table 2.28 Construction Time Breakup

Stages	Duration	Activity
Stage 1	0 - 6 Hr	Digging the Foundations
Stage 2	6 - 11 Hr	Making of Stabilized Rammed Earth foundation
Stage 3	11 - 13 Hr	Building the 1 st course of plinth
Stage 4	13 - 14 Hr	Building the 2 nd course of plinth
Stage 5	14 - 16 Hr	Plinth beam complete
Stage 6	16 - 17 Hr	Filling the basement and starting the wall
Stage 7	17 - 25 Hr	Sill ring beam complete
Stage 8	25 - 30 Hr	Building the Sill
Stage 9	30 - 36 Hr	Lintel ring beam complete
Stage 10	36 - 43 Hr	Roof ring beam complete
Stage 11	43 - 48 Hr	Laying reinforcement channels (Roofing)
Stage 12	48 - 62 Hr	Finishes work

The building was completed in 62 hrs.

Building Specification

The specification of the structure of the AUM House are as under:

Table 2.29 Construction Specification

Sl. No	Structure	Specification
1.	Foundation	Stabilised rammed earth with 5% cement
2.	Plinth	Interlocking Compressed Stabilised Earth Blocks (CSEB) 295 with 5% cement and composite plinth beam - RCC in U Interlocking CSEB.
3.	Flooring	CSEB tiles, 2.5cm thick with screed CS 1:12
4.	Walls	Interlocking CSEB hollow blocks (5%) with reinforcements
5.	Column	Composite - Round hollow CSEB 290 with RCC
6.	Beams & Lintels	Composite (RCC in U interlocking CSEB)
7.	Roof	Interlocking ferro cement channels 1:2
8.	Door	Ferro cement 1:2, 12mm thick
9.	Window Grill	Rod 10 dia TS
10.	Window Shutter	Ferro cement 1:2, 12mm thick

Wall Masonry System

Masonry technology is reinforced masonry with compressed stabilized earth blocks. The wall is constructed out of CSEB blocks applying Auroville's technology. It consists of wall built out of 24cmx24cmx9cm. The wall system has vertical ties at every corner: L-joints and T-joints. Also these are provided on the sides of each fenestration. The continuous wall has vertical tie in every less than 1.5 meters. This is meant for avoiding lateral buckling due to long continuous wall.

There are ring beams in plinth level, sill level, lintel level and roof level. These are connected to the vertical ties to give rigid box effect during earthquake. The ring beams are cast in situ out of U-blocks. The lintels are precast before they are made continuous with the lintel band during actual construction.

All courses are bound by cement stabilized earth mortar 1 cement: 1 soil: 3 sand. It was made plastic and not too liquid. The soil did not have more than 20-25 % of clay. The blocks must be soaked before being laid and a well-laid block is impossible to remove with one hand because it sticks well to the cement sand mortar.

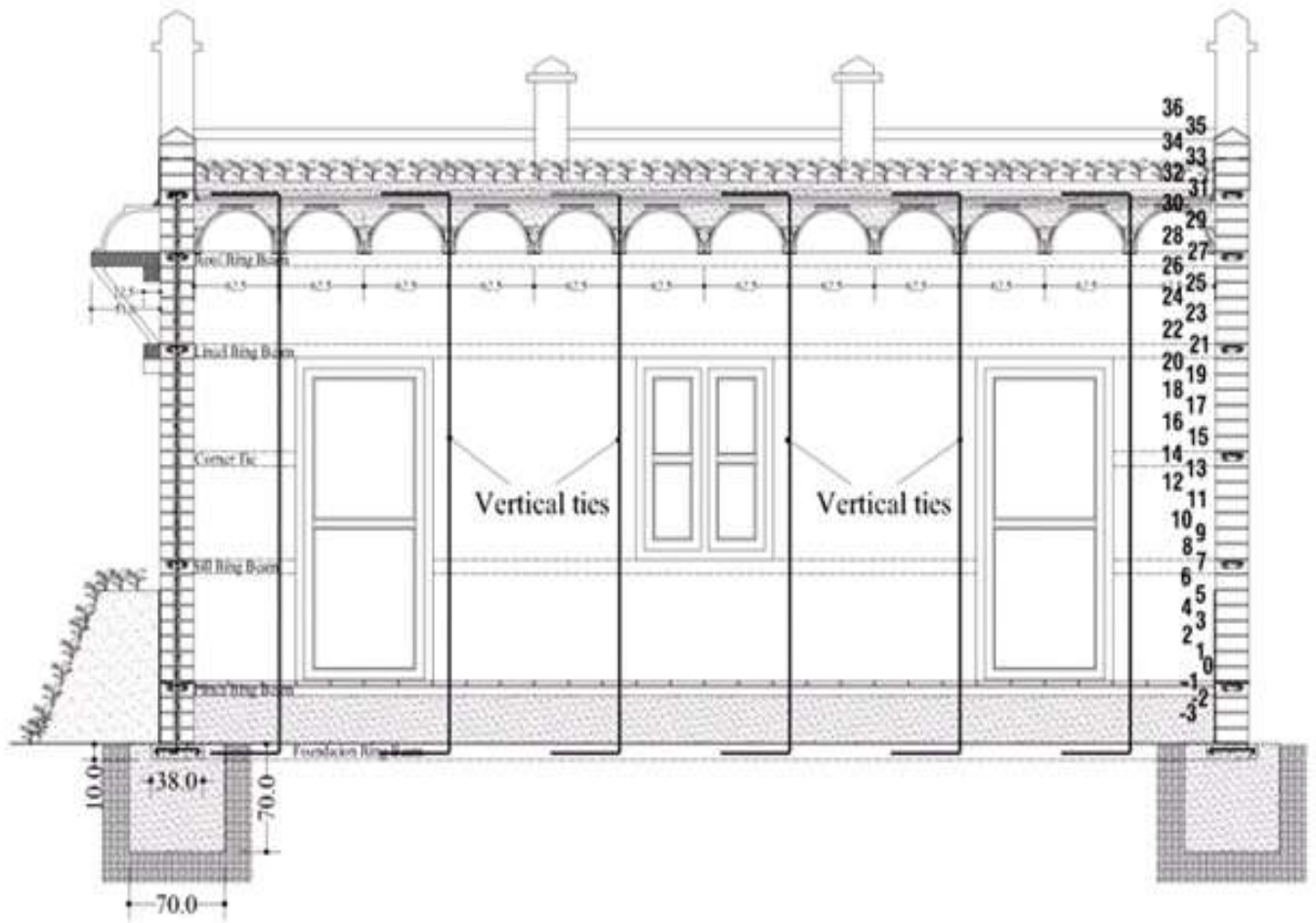


Fig 2.58 AUM House, Gujarat, India - 2001

2.6.3. DESIGN FOR DECONSTRUCTION - COMMUNITY HOUSING RESOURCE CENTER, ATLANTA, GA: CASE STUDY 3

Project: Community Housing Resource Center

Sponsor: U.S. EPA Region 4

Architect: EHDD Architects

Location: 71 Boulevard Atlanta, Georgia

Building Type: Single Family Residential Home

Size: 2,166 ft²

Completion Date: June 2006

Project Goal

This project was conducted as part of the U.S. Environmental Protection Agency's Office of Solid Waste and Emergency Response (OSWER) Innovations Pilot Program. A joint venture between the U.S. Environmental Protection Agency (EPA), Community Housing Resource Center (CHRC) and Pennsylvania State University's Hamer Center, the 71 Boulevard Design for Deconstruction (DfD) house demonstrates that residential homes can be designed both for increased longevity, and for future disassembly and building material reuse. Such characteristics can help decrease the high amount of waste production and resource demands prevalent in the U.S. housing industry today. This is particularly relevant in cities such as Atlanta where high growth rates put pressure on land and material resources to accommodate burgeoning populations. By incorporating techniques such as moveable walls, a disentangled heating and cooling system, and waste reduction, this project demonstrates not only that the environment can benefit from the incorporation of DfD techniques, but that the consumer can as well. Designing a house for near-zero waste means that the owner has increased flexibility and greater ease in reconstruction when carrying out additions and renovations. Funded in part by a \$69,000 grant from the EPA, the project's partners plan to create educational materials around this project to promote the "cradle to cradle" approach for residential building design.

Background

In 2002, the U.S. Geological Survey estimated that 60 percent of all materials flow in the U.S. economy (excluding food and fuel) is consumed by the construction industry.

Preliminary estimates from the EPA in 2003 showed that 91 percent of all construction-related waste produced annually in the U.S. was a result of renovations and demolitions, representing as much as 30 percent of all waste produced in the U.S. Of the total building related waste generated, EPA estimated that only 40 percent was reused, recycled, or sent to waste-to-energy facilities, while the remaining 60 percent was sent to landfills.

it was estimated that the total built space in this country will grow from 296 billion square feet in 2000 to 427 billion square feet in 2030. Of this growth, 82 billion square feet of building will come from the replacement of existing building space and 131 billion will be new construction, totaling 213 billion square feet of new built space. This estimate means that 27 percent of existing buildings in 2000 will be replaced by 2030, and that more than 50 percent of buildings in 2030 will have been built since 2000. Instead of construction materials ending up as waste once these building outlive their usefulness, DfD can be incorporated to recover them from new construction, future renovations and removals.

This case study led to the development of the best practices toolkit for DfD in residential construction, *Design for Disassembly in the Built Environment: A Guide for Closed-Loop Design and Building*. In 2004, the Community Housing Resource Center (CHRC), working in conjunction with the Hamer Center for Community Design Assistance at Pennsylvania State University and EPA Region 4, assembled a group of industry experts for a two-day design meeting in Atlanta, Georgia to develop a design plan for the case study home based on DfD principles. The meeting led to the development of a model for residential DfD construction projects called the “Anywhere House.”

Based on the Anywhere House model, construction of the two-story, 3,000 square foot DfD residential home began in spring 2006 and was completed in June 2006. The pilot documented all research, design, and case study results. In addition, the project team created educational materials promoting the green approach for residential building design and conducted outreach that included discussions with representatives from the American Institute of Architects’ Committee on the Environment, the Used Building Materials Association, and the U.S. Green Building Council.

The case study home featured DfD elements such as repositionable interior walls, which can be removed and relocate without creating any waste or compromising structural integrity; and a disentangled Heating, Ventilation and Air Conditioning (HVAC) system, in which the HVAC system is split into two smaller pumps for heating and air conditioning, one for each floor. This HVAC approach reduces the size of the units and the necessary ductwork, and eliminates the typical entanglement of ducts in the structural core of the second floor, where it would be sealed in by drywall finishes or the sub-floor. This design means that interior wall modifications are less invasive and more easily completed.

The home also included DfD features that focused on the use of green building materials, such as structural insulated panel (SIP) walls made from agricultural fiber that provide a renewable framing and insulating alternative to foam core and wall-to-wall bamboo flooring. Bamboo is not only less expensive and more resilient than typical wood flooring, but it also takes only a few years to reach maturity and can be harvested again and again from the same plant. In addition, the bamboo flooring was installed before the interior walls, which means the floors will not need to be re-patched when walls are moved.

Building Details

The case study home is a two-story, 2,100 ft² residential building constructed on a small 40 by 75 foot, previously undeveloped lot. Located approximately one mile from downtown in the dense urban setting of the historic Martin Luther King, Jr. District of Atlanta, Georgia, this house was designed within the District's strict design regulations. The nearby King Memorial, shops, and restaurants add to the sustainability of the project as a viable home site, and create the potential for a pedestrian friendly urban lifestyle. The site is zoned as live-work and could be used for a home office, a possibility made easier by the home's design for adaptability as well as disassembly.

Project Highlights: Residential Design, Repositionable Walls, And Disentangled Systems

A. Residential Design—A New Medium for Design for Deconstruction

DfD is not a typical process in residential construction; it occurs more commonly in rapidly changing commercial environments such as temporary offices or short-term retail facilities. As such, the 71 Boulevard project is unique to the industry, and had to utilize original approaches and creative thinking to achieve its goals. As one of the first residential DfD projects, a range of adaptations had to be made to the more typical DfD commercial process in order for this project to succeed. For instance, standard DfD design incorporates a prefabrication strategy, using off-site labor and higher levels of technology. However, such high-tech conditions are not common in the residential construction industry, where the vast majority of homes are built on-site. Choosing to work within current residential construction DfD constraints in order to complete the project, project managers focused on building the homes first for adaptability (i.e. moveable walls), and second for future disassembly, rather than the typical primary emphasis on disassembly. Adaptability can be readily appreciated by everyday homeowners and effectively communicated to

subcontractors on the project. In addition to being on the forefront of incorporating DfD into residential home design, this pilot project was a successful learning tool for testing the viability of DfD in the market, both by working with a traditional construction company, and by selling the home on the open real estate market.

B. Repositionable Interior Walls

With its repositionable interior walls, the 71 Boulevard house incorporates a unique system of adaptability for residential construction. Repositionable walls are significantly different from the traditional stick framing home design, in which interior walls are necessary to hold up the roof. Any changes to wall arrangements in this traditional design not only destroy the wall materials, but create structural problems that often result in the generation of substantial waste materials through extensive re-framing or, in some cases, demolition because the home requires too much remodeling to meet new space needs. In contrast, the repositionable interior walls in this home can be removed and relocated without creating any waste or compromising structural integrity. They are created using a light-gauge metal to frame the wall panels and reduce weight for portability, and a system of wood base plates and top and bottom trim pieces. When finished, each steel framed and drywall covered panel of the non-loadbearing wall can be removed individually. The wall sections can then be reused as is, or combined to create new configurations to meet the homeowner's needs. In fact, since 71 Boulevard was built, its current owner has already remodeled the downstairs to allow for a home business space, generating no waste in the process.

C. Disentangled Heating and Cooling Systems (HVAC)

Another successful DfD strategy in this project involved splitting the HVAC system by using two smaller heat pumps for air conditioning, one each for the first and second floor, rather than a single large pump. This approach has several benefits. First, it reduced the size of the units and the necessary ductwork. Second, by splitting the system, locating one in the basement crawlspace to control the first floor and one in the attic space to control the second floor, this approach eliminated the typical entanglement of ducts in the “core” of the structural zone of the second floor, where it would be sealed in by drywall finishes or sub-floor. Instead, both the crawlspace and attic allow for better system access. This design means that interior wall modifications are less invasive and more easily completed, as they will not involve maneuvering around or reconfiguring the systems. In addition, this HVAC strategy is a more energy efficient and affordable option.



Fig 2.59 Existing Plan

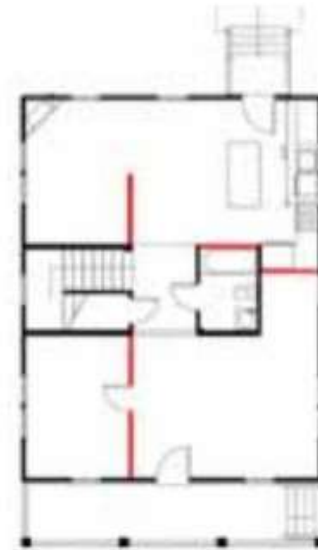


Fig 2.60 Future Proposed Plan



Fig 2.61 Existing Building

2.6.3. HAENER HOUSE IN NAPA, CALIFORNIA: CASE STUDY 4

Project:	Low Cost Housing
Location:	Napa, California
Construction Duration:	1 day
Interlocking Block:	Haener Block
Area:	350 sqft
Year:	2003

The Haener block is used to construct a house of area 350 sqft, located at Napa in California. The house was constructed in a single day by using unskilled labour. "We wanted to simulate how low cost housing is often built in 3rd world countries using unskilled laborers and at- hand equipment and materials." said Ron Shepersky, a Napa general contractor and customer of Haener Block.

The completed Haener Home was an 850 sq. ft. two bedroom house with 8 ft. high solid block interior and exterior walls. Installation of electrical and plumbing was demonstrated but not completed for the event, and the foundation was poured in advance.

The eight foot exterior and interior walls were constructed in just three hours by five unskilled workers in Napa, California on June 3, 2003. The first four feet height of the interior and exterior wall was completed in just 1 hour by using just 2 unskilled workers and representative from Haener block company. The workers were able to construct upto 10 blocks per minute which is nearly 10 times higher than the conventional block laying.

Haener Block, the mortarless, interlocking, self-aligning block system was invented by Dr. Juan Haener, world renown physicist. The blocks used for this project were supplied by Mission Concrete Products of San Jose. Haener block is licensed in 20 countries The Mexican licensee plans to build 17,000 houses in Puebla, Mexico. According to tests by the National Concrete Masonry Association, the Haener block is ten times stronger in shear strength than a mortared block since the weakest part of the structure is the mortar.

Haener has an insulated block and, for withstanding hurricanes and earthquakes, a footer block and interlocking pilaster.



Fig 2.62 Haener House, Napa



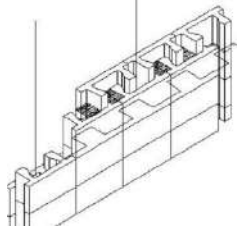
Fig 2.63 Haener House, Napa - Construction

2.7 Literature Review Summery

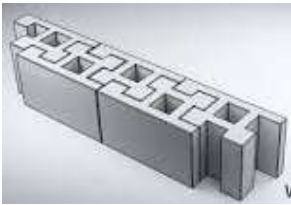
2.7.1 Summery of Properties of Interlocking Blocks

Sl. No	Interlocking Block Type	Details	Properties	
1	Connex Interlocking Block System (US) 	Material	Concrete	
		Geometry	Hollow	
		Size	Height	200 mm
			Thickness	150/200 mm
			Length	400 mm
		No. of blocks per sqm	12.5 blocks	
		No. of course per meter	5 courses	
		Type of units	3 units (Stretcher, corner/ end, Half)	
		In-Site Production	No	
		Fire Rating	150mm thick wall (with grout)	3 hours
			200mm thick wall (with grout)	4 hours
		Compressive Strength	15 MPa or 15 N/mm ²	
		Sound Rating	50 RW	
		Load Bearing	Yes	
		Plastering Required	No	
2	Interlocking Stabilized Soil Block (ISSB) (Thailand by TISTR) 	Material	Sand, Laterite (Containing sand/silt and clay) and cement	
		Geometry	Semi Hollow	
		Types of Units	3 Units (Stretcher/full block, half, channel)	
		In-Site Production	Yes	
		Size	Height	100 mm
			Thickness	125 mm (150 mm)
			Length	250 mm (300mm)
		Compressive Strength	6.86 Mpa or 6.86 N/mm ²	
		Water Absorption	Less than 15 %	
		No. of course per	6.6 course	

		meter		
		Grout Mortar	Portland cement to sand=1:2 (w/c - 0.75) Cement to sand=1:3 (w/c - 1)	
		Load bearing	Yes	
		Max Wall Height	4.5 m	
		Reinforcement	Vertical Only (Core filled)	
		Grouting Height	10 Course	
		Plastering Required	No	
3	Flexlock Concrete Interlocking Units (in US by Cercorp Initiatives Inc) 	Material	Concrete	
		Geometry	Hollow	
		Size	Height	8 inch (200 mm)
			Thickness	8 inch (200 mm)
			Length	16 inch (400 mm)
		Compressive Strength	6.48 MPa	
		Density	97.8 pcf	
		Water Absorption	8.8 %	
		Fire Rating	2.37 Hours (142 minutes)	
		Labour Productivity	1 labour - 120 blocks per hour	
		Thermal Resistance	6.182 to 10.28 hr ft ² F/Btu	
		No. of course per meter	6.6 course	
		Reinforcement	Post Tension Tendon Reinforcement with Grout (optional)	
		Plastering Required	No	
		Load Bearing	Yes	
		In-Site Production	No	
4.	IITM-HILBLOCK System (Hollow Inter-Locking BLOCK) (Madras, India)	Material	Concrete	
		Geometry	Hollow	
		Size	Height	200 mm
			Thickness	200 mm + 40 mm
			Length	400 mm
		Reinforcement	Vertical (core grouting filling optional), Horizontal (Rod bent to match the shape)	
		Load Bearing	Yes	
		Plastering Required	No	

		Compressive Strength	10.71 MPa			
		In-Site Production	No			
		No. of course per meter	5 course			
5.	Interlocking Stabilised Soil Blocks (ISSB) (Africa) 	Material	Soil, cement and stabilizer (cement/lime/fibrous/chemical/raisins)			
		Geometry	Solid			
		Size	Height	100 mm		
			Thickness	140 mm		
			Length	265 mm		
		Weight	8 - 10 Kg			
		Texture	Smooth and Flat			
		No. of blocks per sqm	35 blocks			
		Compressive Strength	1 - 4 MPa (Block), 2.5 - 6.7 MPa			
		Thermal Insultation	0.8 - 1.4 W/mC			
		Density	1700 - 2200 Kg/cum			
		In-Site Production	Yes			
		Plastering Required	No			
		Load Bearing	Yes			
		Reinforcement	No			
6.	Auram Hollow Interlocking Blocks (in India by Auroville) 	Material	Soil, cement			
		Geometry	Semi-hollow			
		Size (3 Types)	Height	100mm	100mm	100mm
			Thickness	250mm	250mm	150mm
			Length	250mm	300mm	300mm
		Compressive Strength	7.35			
		Density	1732 Kg/cum			
		Water Absorption	11%			
		No. of Storey	2 storey (8m height max)			
		Reinforcement	Vertical (core grout fill)			
		In-Site Production	Yes			
		Plastering Required	No			
Load Bearing	Yes					
No. of course per meter	10 course					

7.	Haener Block 	Material	Concrete	
		Geometry	Hollow	
		Size	Height	8 inch (200 mm)
			Thickness	8 inch (200 mm)
			Length	16 inch (400 mm)
		Types of Units	3 Units (stretcher, corner/end, half block)	
		Weight	34 Pound (15.4 kg)	
		Labour Productivity	1 labour - 100 blocks per hour (800/day)	
		Reinforcement	Horizontal and vertical (core filled)	
		In-Site Production	No	
		Plastering Required	No	
		Load Bearing	Yes	
		No. of course per meter	5 course	
		Density	2082 kg/m ³	
		Compressive Strength	10.75MPa	
8.	Smart Masonry System (Australia) 	Material	Concrete	
		Geometry	Hollow	
		Size	Height	200 mm
			Thickness	140 mm / 110 mm
			Length	400 mm
		Types of Units	3 Units (stretcher, corner, end)	
		Weight	10.5 kg - 13.5 kg	
		Compressive Strength	3.45MPa to 20.68Mpa	
		Grout Mortar	Cement to sand = 1:5 (w/c - 1)	
		Reinforcement	Horizontal and vertical (core filled)	
		No. of course per meter	5 course	
		In-Site Production	No	
		Plastering Required	No	
9.	Azar Dry Stack Block (Canada)	Material	Concrete	
		Geometry	Hollow	

		Size	Height	8 inch (200 mm)
			Thickness	8 inch (200 mm)
			Length	1'4" (400 mm)
		Types of Units	1 Units	
		Weight	17.9 kg	
		Density	2075 kg/cum	
		Water Absorption	6.85%	
		Compressive Strength	33.4 MPa	
		No. of course per meter	5 course	
		In-Site Production	No	
		Plastering Required	No	
		Load Bearing	Yes	
		Reinforcement	Horizontal and vertical (core filled)	
		Interlocking Mechanism	Tongue and groove	
10	Sparlock Block Masonry System 	Material	Concrete	
		Geometry	Hollow	
		Size	Height	200 mm
			Thickness	150 mm
			Length	400 mm
		Density	2248 kg/cum	
		Weight	10.87 kg to 11.25 kg	
		Compressive Strength	6.92 MPa to 28.4 MPa	
		No. of course per meter	5 course	
		In-Site Production	No	
		Plastering Required	No	
		Load Bearing	Yes	
		Reinforcement	Horizontal and vertical (core filled)	
		Interlocking Mechanism	Tongue and groove	

2.7.2 Summery of Literature Case Studies (For Interlocking Blocks)

Sl. No	Details	Case Study 1	Case Study 2			Case Study 3
1.	Project Name	FlexLock House	Disaster Resistant House			Haener House
2.	Project Location	Magnolia, Texas	Istanbul	New Delhi	Gujarat	Napa, California
3.	Year	2006	1996	1999	2001	2003
4.	Building Type	Residence	Residence			Residence
5.	Building Scale	Single Storey	Single Story			Single Storey
6.	Building Area	2958 sqft	9 sqm	23 sqm	28 sqm	350 sqft
7.	Type of Interlocking Blocks Used	FlexLock Interlocking block system	Auram Hollow Interlocking blocks by Auroville			Haener Interlocking Blocks
8.	Need for the Project	House constructed as an experiment for comparing FlexLock system with conventional masonry system	The disaster resistant housing was required to rehabilitate people affected by earthquake and tsunami			House conducted to test the performance of Haener blocks
9.	Aim of the Project	Execute project as per the FlexLock system in cost effective and time effective manner. Implement design for deconstruction	Construct quick and simple housing unit that are portable/movable and can resist earthquake. The construction must be cheaper, less labor intensive and easy executable.			Construct house in the quickest time with unskilled labour.
10.	Stakeholders of Project	Client/Owner	Cercorp Initiatives Inc			-
		Sponsor	Cercorp Initiatives Inc	UNCHS/HABITAT	HUDCO	-
		User	Cercorp Initiatives Inc	Disaster Victims		-
		Architect	CAD-FM Design Architecture Firm	-		-

		Engineer/ Structural	Ryan-Biggs Associates	-			-
11.	Duration of Construction		4 days	8 days	66 hours	62 hours	1 day
12.	Labour Involved		Unskilled labor	Semi-skilled Labor			Unskilled Labor
13.	Labour Productivity		164 blocks per hour per man (increased productivity by 100%)	-	18 men	20men	60 blocks per hour per man (5 men)
14.	Cost Efficiency		24% cost savings	-			-
15.	Benefits attained by use of Interlocking Blocks		▪ Reduce Cost ▪ Rapid on-site construction ▪ Use of unskilled labor ▪ Superior seismic and wind performance ▪ All season construction ▪ Can be disassembled and build again	▪ Reduce Cost ▪ Rapid on-site construction ▪ Use of unskilled labor ▪ Superior seismic and wind performance ▪ All season construction ▪ Can be disassembled and build again ▪ Reinforced wall using interlocking blocks			▪ Reduce Cost ▪ Rapid on-site construction ▪ Use of unskilled labor ▪ performance ▪ All season construction ▪ Can be disassembled and build again
16.	Advantages of FlexLock Wall System		▪ Mortarless except 1st course ▪ Reduced construction time ▪ Required less skilled labour - adapt to existing labor	▪ Mortarless except 1st course ▪ Reduced construction time ▪ Required less skilled labour - adapt to existing labor pool ▪ Completely reusable ▪ All season construction ▪ Super strong wall			▪ Mortarless except 1st course ▪ Reduced construction time ▪ Required less skilled labour - adapt to existing labor

		- pool ▪ Completely reusable ▪ All season construction ▪ Super strong wall ▪ Reduced construction time	▪ Reduced construction time ▪ Earthquake resistant structure ▪ Portable structure	- pool ▪ Completely reusable ▪ All season construction ▪ Super strong wall ▪ Reduced construction time ▪ Portable structure ▪ Withstand hurricanes and earthquake
17.	Cost Savings - Cause	▪ Unskilled labor ▪ Quick construction ▪ No Mortar ▪ No Grout	▪ Unskilled labor ▪ Quick construction ▪ No Mortar	▪ Unskilled labor ▪ Quick construction ▪ No Mortar
18.	Labour Saving - Cause	▪ Skilled labour for 1st course only ▪ Unskilled labour for all other construction ▪ Instead of conventional 3 mason requirement, one mason and 2 helper are enough	▪ Skilled labour for 1st course only ▪ Unskilled labour for all other construction ▪ Participation of volunteers ▪ Pre-casting of blocks is done in Auroville and transported to site ▪ The precast blocks are just assembled at site	▪ Skilled labour for 1st course only ▪ Unskilled labour for all other
19.	Cycle time for laying 1 block	20 seconds	-	-
20.	Interlocking	Dry stacking of	Dry stacking of interlocking	Dry stacking of

	Block system	block with post tension tendon reinforcement	block with vertical reinforcement & horizontal ties at regular intervals.	interlocking block with wall vertical reinforcement
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CHAPTER 3

LIVE CASE STUDY

3.1 RESIDENCE OF DIVYA SHAMANTH, BANGALORE

PROJECT DETAILS	
Client	Divya Shamanth
Location	Anjanapura, J P Nagar, Bangalore, India
Interlocking Block Manufacturer	Earth Blocks India Pvt. Ltd. at Bangalore
Interlocking Block Name	Compressed Stabilised Earth Blocks - Hollow interlocking block
Block Size	300mm x 150mm x 90mm
Building Type	Residence
No. of Floors	G+ 4
Site Area	1200 sqft (40ft x 30ft)
Floor Area	3576.90 sqft
Structure Type	Framed Structure with Interlock Block Masonry wall
Slab Type	Filler Slab
Sub-Structure	Isolated Footing with pillar and earth beam.
Project duration	2017



Fig 3.1 Residence Of Divya Shamanth, Bangalore

3.1.1 Specification Of Hollow Interlocking Block (CSEB)

- a) Material: soil block stabilized with cement (6-8% cement by weight)
- b) Production: Machine made, Compressed using Hydraulic Press
- c) Finish: Surface has smooth finish and borders are straight. Edges are bevelled and sharp
- d) Interlocking Type: Dry Interlocking (No mortar between brick courses). Mortar is poured as slurry in the holes to achieve interlocking
- e) Colour: Varying shades of earth
- f) Size: L x W x H (300x150x90mm) or (1ft x 6in x 3.5in)
- g) Compression Strength: More than 12 MPa (120 Kg/cm²)
- h) Water absorption: 5-8% by weight
- i) Bulk density: 1900 - 2000 Kg/m³
- j) Carbon emission (CO₂/m³ raw material): Very low
- k) Others: Fire proof, bug proof, sound proof
- l) Max Variation: 1mm



Fig 3.2 Compressed Stabilized Earth Block (CSEB) by Earth Blocks India Pvt. Ltd

3.1.2 Need for Interlocking Block in Project:

- a) Client needed low cost construction option
- b) Need traditional construction technology
- c) Needed traditional look and feel to the project - warm and cosy
- d) Embrace sustainability principles
- e) Use locally available material
- f) Good indoor quality for home
- g) Quick construction
- h) Organic and breathing space

3.1.3 Achievements by using Interlocking Block in Project:

- a) Reduced labour requirements
- b) Reduced usage of cement, sand, water

- c) Increase speed of construction
- d) Eco friendly as block is compressed instead of burnt and soil is eco friendly and sustainable
- e) Unskilled labour used for construction, labour cost reduced
- f) Construction is earth quack resistant
- g) Passive cooling is achieved as interior is cooler compared to outside
- h) Earthen blocks are non-toxic, long lasting, dirt is reusable

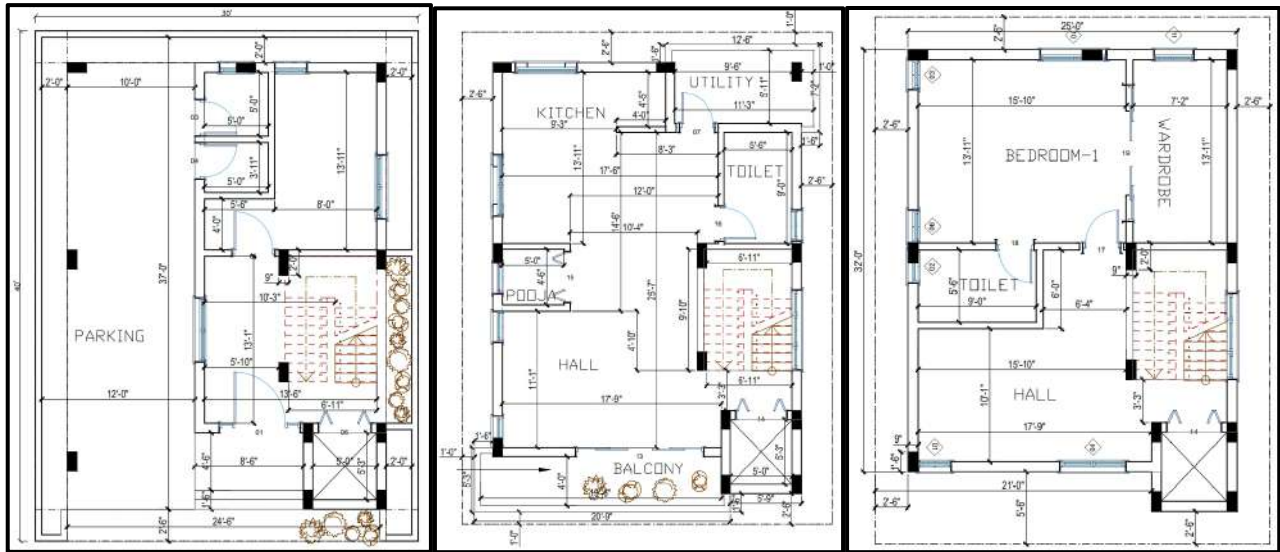


Fig 3.3 Ground Floor, First Floor and Second Floor Plan

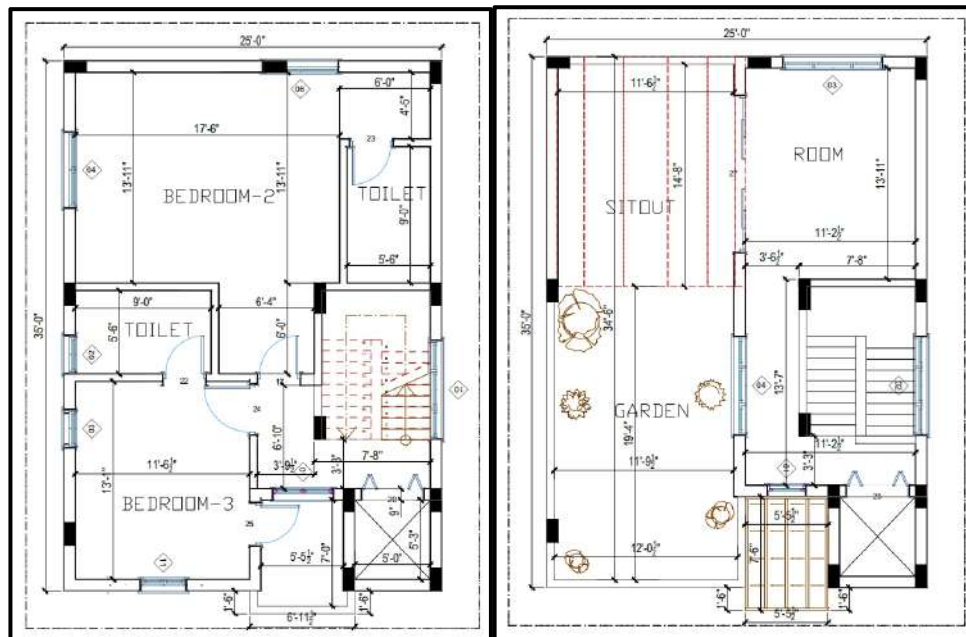


Fig 3.4 Third Floor and Fourth Floor Plan

3.1.4. Making of Interlocking Block

Compressed Earth Blocks are made by compressing Silt, Clay & Sand along with 8 % Portland cement (used as a stabilizer) in a hydraulic press. These blocks can be used to build with after curing for 7 days. They reach full strength and become water-resistant after a 21-day curing period.

3.1.5 Equipment Needed for Construction

- a) Mason Trowel
- b) Bricklayer's Hammer
- c) Joint Filler
- d) Square Trowel
- e) Plumb Bob
- f) Metal Float
- g) Right angled Scale
- h) 2ft spirit level
- i) Angle grinder
- j) Cut-off machine to cut the blocks
- k) Rubber Hammer to adjust the blocks
- l) Drill machine to fix the rebar to the plinth beam
- m) Brush

3.1.6 Stakeholders Involved

Client	Divya Shamanth
Architect	Ar. Divakar
Interlock Block Manufacturer	Earth Blocks India Pvt. Ltd. at Bangalore
Structural Designer	shivaraju
Doors and Windows	Lingel India (UPVC windows)
Contractor	Gauri Constructions
Poured Earth prep team	Arul & Team @ Jothi Constructions
Master Craftman	Mr. Ayyanar
Site Supervision	Guddegueda

3.1.7 Construction Techniques

In the study, the masonry techniques used in the project are studied.

3.1.7.1. Sub Structure:

Foundation is conventional isolated RCC foundation. The plinth beam is at 6" above existing ground level as interlocking blocks can not be trusted to be used for underground construction.

3.1.7.2. Damp proof course:

DPC is very important in interlocking block construction as capillary rise of water and dampness from ground has to be stopped to protect the masonry walls. The DCP has to be laid before starting the 1st course of the interlocking block.

3.1.7.3. First course of Masonry system

The 1st course of interlocking block use cement motor to bind the blocks together. Drills are made in plinth beam to insert rods at every 1-1.5m.

3.1.7.4. Other Interlocking Block course:

The 2nd interlocking block course are arranged in self-aligning linear manner with no use of cement. The top projecting double circles align perfectly with the next top course, thereby they lock perfectly. It is hammered with rubber hammer to make sure the block is interlocked and settled perfectly. After 4 course of interlocking block, a slurry mix of cement and sand with water is poured into the interlocking block holes to make sure the blocks are sealed. This ensures that the blocks are locked in both horizontal and vertical direction.

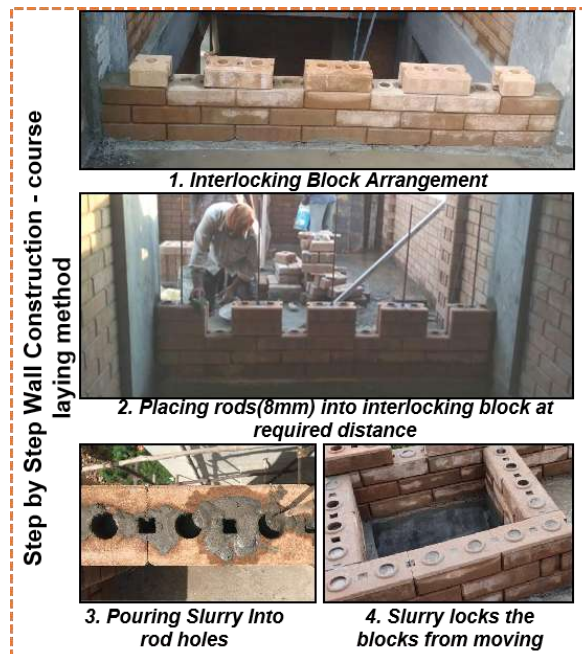


Fig 3.5 Construction Technique of IB course placement

3.1.7.5. Electrical & Plumbing Conduits:

In conventional system, the conduit laying for walls are done after the masonry works are completed. But in interlocking blocks, the conduits are laid simultaneously as the blocks are arranged. The conduits are inserted into the holes in interlocking blocks as they are arranged one on top of the other. Electrical chase is not required unless in special cases. No separate duration is needed for electrical conduiting in masonry walls.



Fig 3.6 Construction Technique of IB MEP Services

3.1.7.6. Connecting 300mm wall and 150mm wall (Mainly Parapet wall):

The grooves and the geometry of the interlocking block make it not suitable to connect the 300mm wall and 150mm wall without external connections and bondings.



Fig 3.7 Construction Technique of IB Wall Connections

3.1.7.7. Lintel Beam :

In interlocking block, U-block is available for casting lintel beam. But, in this project, there is no lintel beam provided. Sill beam is also not provided. In this project, Lintel beam is provided using U-block in which reinforcement rods are laid and concrete is poured on top to create a load transferring structure above window and door opening. The reinforcement is collected to column for through-lintel.



Fig 3.8 Construction Technique of IB - Lintel using U-Block

3.1.7.8. Floor/Roof Slab:

The shallow clay pot filler slab is provided for light weight construction. The use of filler slab can reduce the transfer of load to load bearing walls and structures. They give good look and good insulation against heat.



Fig 3.9 Construction Technique - Filler Roof Slab

3.1.7.9. Doors and Windows:

The doors and windows used are UPVC windows. They are drilled into the plaster and block and screwed into place. The opening are plastered with 2 inch of plaster creating a protective layer around blocks. This prevent water from entering into blocks.

3.1.7.10. Wall finishing:

The pointing is done using soil cement paste. On top of the pointing, nano particle based water proofing painting is done. Damp proofing and water proofing is very important in interlocking blocks.



Fig 3.10 Construction Technique - Pointing and Water Proofing

3.1.7.11. External Column, Beam & Block Connection Plastering for Damp Proofing:

In this project, the connections between column and beam is plastered and sealed. There is a chance of water seepage and dampness entering into building from exterior because of possible gaps between beam and block top and column and block, the connections are plastered on the outside with sealing cement mortar. There plastering also create aesthetic view and design element to the building.



Fig 3.11 Construction Technique - External Plastering

3.1.7.12. Arch Opening using Interlocking Block:

In Terrace floor, openings are created in arch pattern using interlocking blocks. The arch is created using metal rod arched into required shape and interlocking blocks are inserted through it. They add an aesthetic element to the building.



Fig 3.12 Construction Technique - Arch Opening

3.1.7.13. Fixing of Compound Wall Entry Gate:

The compound gate is fitted to a MS post instead of interlocking block itself. The MS post is later covered with interlocking block. Interlocking block is not fit for carrying the gate weight and connections.



Fig 3.13 Construction Technique - Compound Gate Fixing

3.1.7.14. Jalli Wall Using Interlocking Block

The jalli wall works was created using the interlocking block by using holes in interlocking block as jalli gaps. The project used jalli walls for pooja room walls, internal partitions and compound wall.



Fig 3.14 Construction Technique - Jalli Wall

3.1.8 Detail Drawing

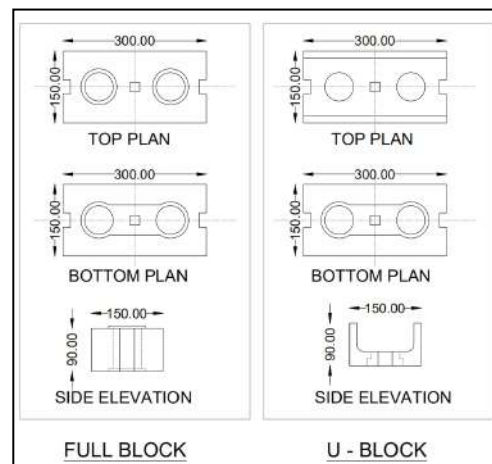


Fig 3.15 Interlocking Block Units Type

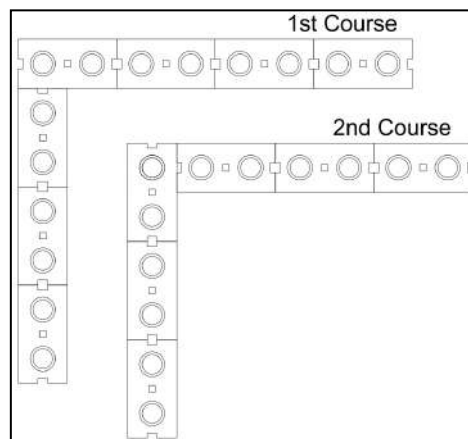


Fig 3.16 Interlocking Block Course Arrangement

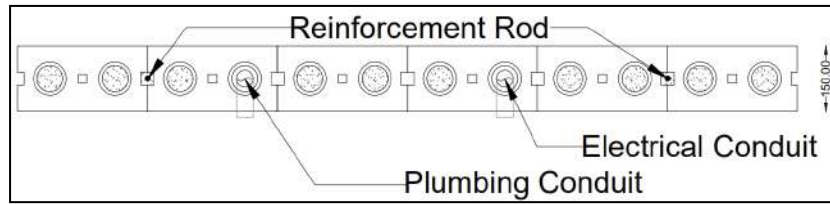


Fig 3.17 Plumbing and Electrical Conduit Detail

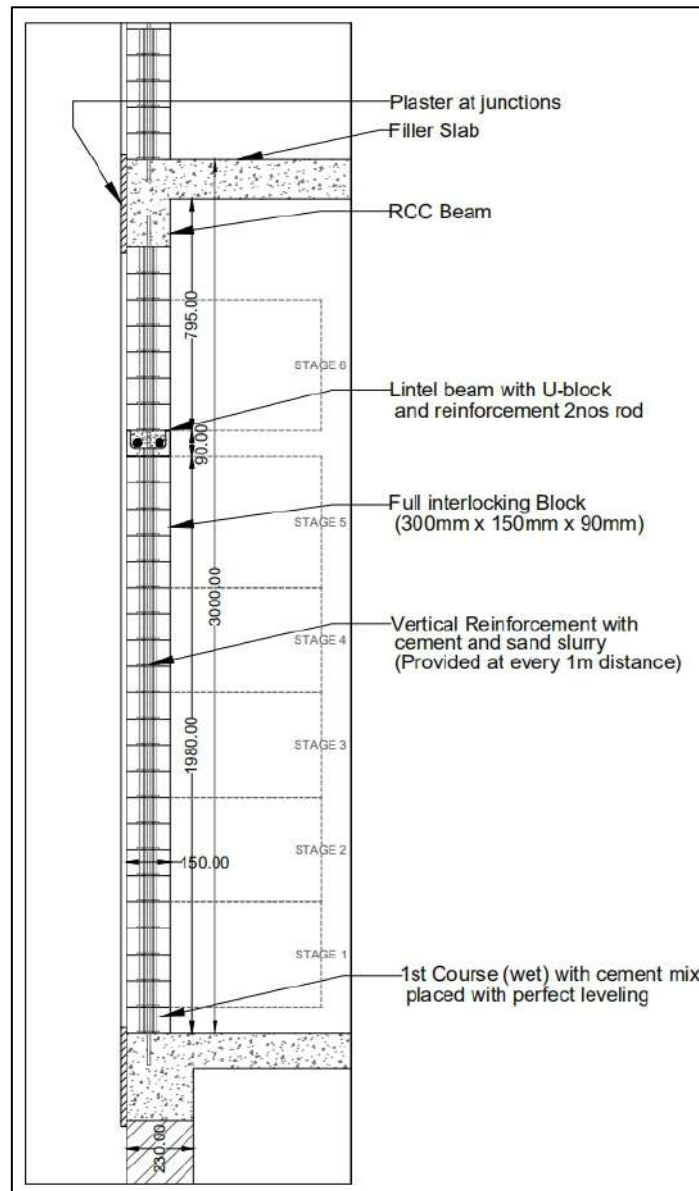


Fig 3.18 Wall Section Detail

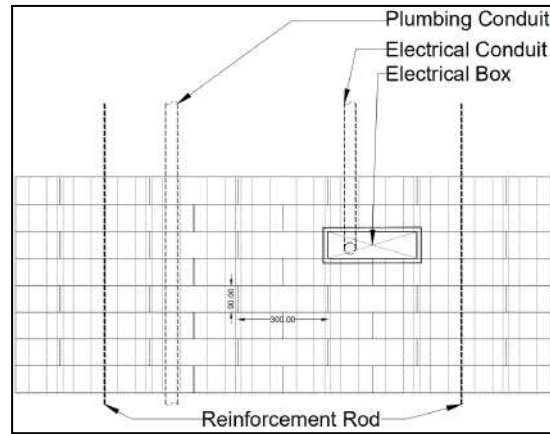
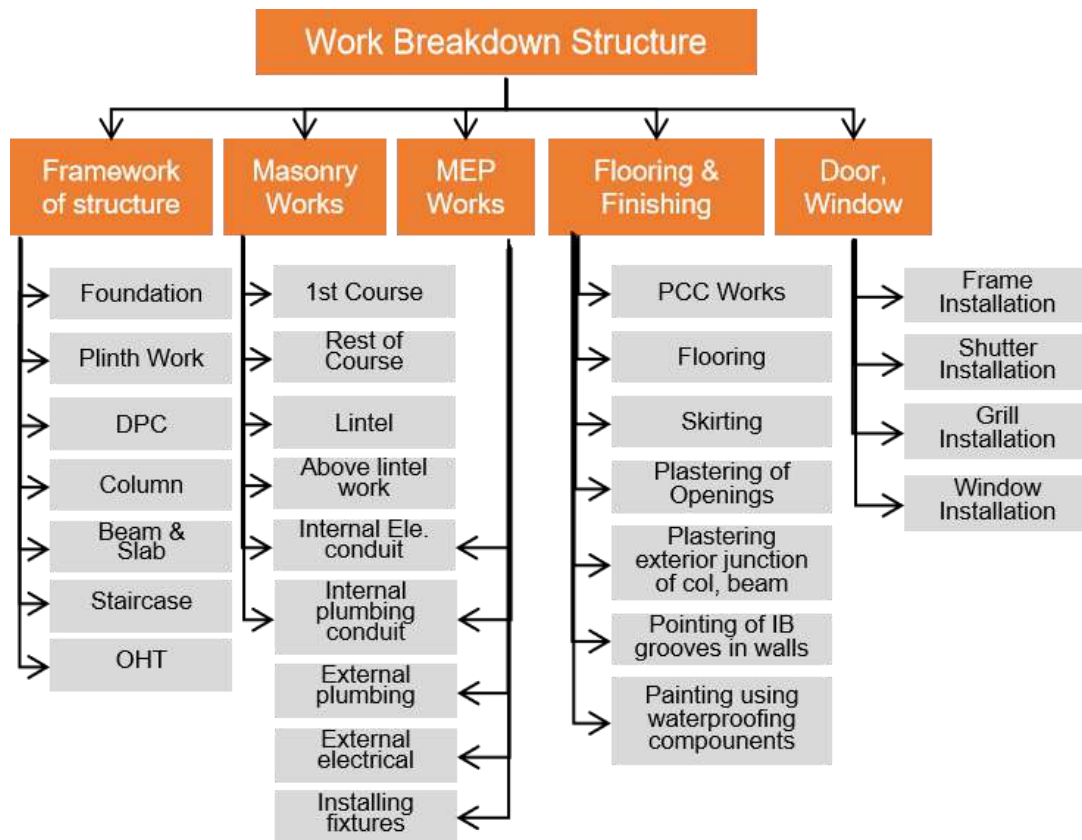


Fig 3.19 Interlocking Block - Wall Elevation

3.1.9 Work Breakdown Structure



3.1.10 Comparison of Interlocking Block with Brick Masonry Construction

Sl. No	Activities	Conventional Construction using brick	Interlocking Block Construction	Remarks
1.	Foundation and Plinth Works	₹ 7,97,653.76	₹ 7,97,653.76	The foundation and plinth shall be same
2.	RCC Works - Super Structure	₹ 16,49,691.20	₹ 16,49,691.20	The RCC super structure shall be same
3.	Masonry Works	₹ 7,15,274.24	₹ 18,92,385.916	The brick masonry system is replaced by IB masonry system.
4.	Plastering	₹ 3,32,484.62	₹ 1,57,056.20	The plastering is done for beam, column, slab, openings
5.	Painting	₹ 4,52,594.39	₹ 84,556.81	Only water proofing/damp proofing paint is provided in interlocking block construction. Other painting is not required.
6.	Flooring	₹ 6,18,260.68	₹ 6,18,260.68	The flooring used be same
7.	Door and Windows	₹ 5,69,956.01	₹ 5,69,956.01	The doors and windows used shall be same
8.	Steel Works	₹ 68,120.00	₹ 68,120.00	The steel works shall be same
9.	MEP Works - Plumbing	₹ 5,20,403.49	₹ 5,20,403.49	The plumbing works cost shall be same
10.	MEP Work - Electrical	₹ 5,20,403.49	₹ 5,20,403.49	The electrical works shall be same
TOTAL COST OF CONSTRUCTION		₹ 62,44,841.89	₹ 68,78,487.556	The cost of construction is high for IB system compared to brick in high rise building due to reinforcing the IB walls.
COST PER SQFT		₹ 1746.00/sqft	₹ 1923.03/sqft	

Note: The cost is not inclusive of OHT, UGS, compound wall, lift and other additional works

3.1.11 Material and Labour Cost Analysis

Description	Quantity	Rate	Amount
Labour cost per m³ for Brick			
Mason (brick layer) 1st class	0.47 day	₹ 900	₹ 423
Mason (brick layer) 2nd class	0.47 day	₹ 850	₹ 399.5
Coolie	1.8 day	₹ 600	₹ 1080.00
Bhisti	0.2 day	₹ 600	₹ 120
Total Labour cost per m³ for brick			₹ 2022.50
<i>Note: Referred from DAR (Civil), 2018. Labour rate is taken as per market rate in Chennai</i>			

Description	Quantity	Rate	Amount
Labour cost per m³ for Interlocking Block (CSEB)			
Mason (brick layer) 1st class	0	₹ 900	0
Mason (brick layer) 2nd class	0.3 day	₹ 850	₹ 255.00
Coolie	0.3 day	₹ 600	₹ 180.00
Bhisti	0	₹ 600	0
Total Labour cost per m³ for brick			₹ 435.00
<i>Note: Referred from DAR (Civil), 2018. Labour rate is taken as per market rate in Chennai</i>			

Description	Quantity	Rate	Amount
Material cost per m³ for Brick			
Brick Units	494 units	₹ 8.00	₹ 3952.00
Cement mortar 1 : 6	0.25 cum	₹ 3217.50	₹ 804.37
Scaffolding	1.13 day	₹ 368.00	₹ 415.84
Water	-	-	₹ 50.00
Total Material cost per m³ for brick			₹ 5222.21
<i>Note: Referred from DAR (Civil), 2018. Material rate is taken as per market rate in Chennai and DAR rates</i>			

Description	Quantity	Rate	Amount
Material cost per m³ for Interlocking Block (CSEB)			
Brick Units	247 units	₹ 30.00	₹ 7410.00
Cement mortar 1 : 6	0	₹ 3217.50	0
Scaffolding	1.13 day	₹ 368.00	₹ 415.84
Water	0	0	0
Total Material cost per m³ for brick			₹ 7825.84
<i>Note: Referred from DAR (Civil), 2018. Material rate is taken as per market rate in Chennai and DAR rates. The IB is assumed to be dry stacked.</i>			

Items	IB Wall	Brick Wall
Price Per Unit	₹ 30.00	₹ 8.00
Amount of units per m³	247 nos	494 nos
Labour per m³	₹ 435.00	₹ 2022.50
Cement mortar (1:6) per m³	-	0.25 cum

Masonry System	Material Cost per m³	Labour Cost per m³	Total Cost per m³
Brick	₹ 5222.21	₹ 2022.50	₹ 7244.71
Interlocking Block (CSEB)	₹ 7825.84	₹ 435.00	₹ 8260.84

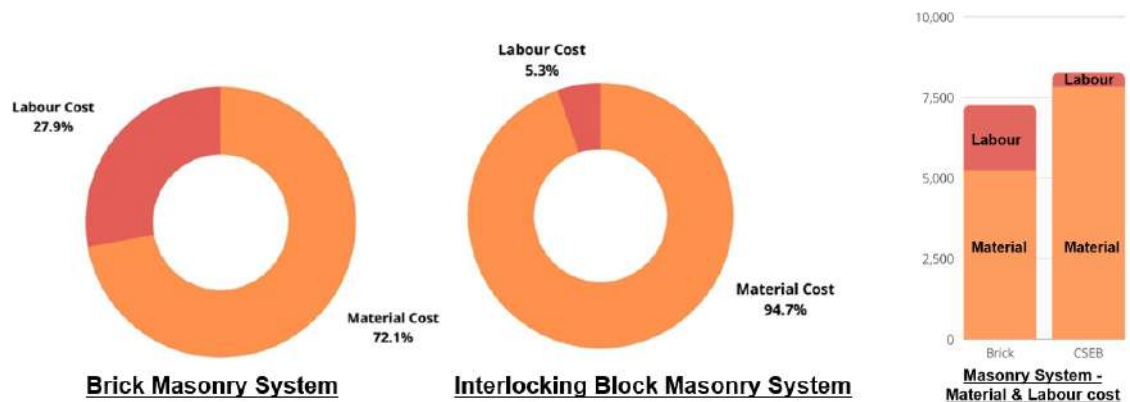


Fig 3.20 Interlocking Block vs Brick Masonry System

3.1.12 Cycle Time Analysis

Table 3.1 Cycle Time of Laying Interlocking Block

No	Task	Description	Time	Assumption & Comments
1.	Fetch	Retrieve unit from cube	4 sec	The unit is placed within 10' proximity to the labour
2.	Lift	Pick up unit	2 sec	Using established OSHA Standards
3.	Return	Go back to the wall	4 sec	The unit is placed within 10' proximity to the labour
4.	Inspect	Look over block	2 sec	Examine for imperfection
5.	Check	Check surface for debris	3 sec	Quick visual look at bed joint
6.	Clean	Remove debris	1 sec	This is rarely the case
7.	Lay	Place block on the wall	2 sec	Ensure proper orientation
8.	Seat	Rock to secure	2 sec	Reducing the possibility of point loading
9.	Set	set using rubber hammer	4 sec	careful setting to avoid later settlement
Per cycle time in seconds			24	

3.1.13 Construction Methodology Comparison

Table 3.2 Comparison of Construction Methods

Details	Conventional Brick Masonry	CSEB interlocking Block (Live Case Study - 1)	Alternative Method for CSEB Interlocking Block (upto G+1 Only)
Foundation	Isolated/combined RCC footing	Isolated/combined RCC footing	Isolated/combined RCC footing
Earth/Plinth/ Tie beam	RCC Beam at required level	RCC Beam at 4"-6" above existing ground level to protect IB from constant dampness and contact with earth	Earth beam required above existing ground level
Plinth Filling	Normal filling with anti-termite treatment and sand layer below PCC flooring	Normal filling with anti-termite treatment and sand layer below PCC flooring	Plinth filling same with anti-termite treatment.
Structure	Framed structure - Column and beam	Framed structure - Column and beam	Framed structure - Column and beam
Floor/Roof Slab	Slab is RCC slab with reinforcement	Light weight Filler slab with shallow clay pots	Light weight slab options - filler slab, composite floor slab, pre-cast slab
Masonry Wall	1st course above DPC and all course with cement mortar	1st course above DPC use cement mortar and other course dry stacked with cement slurry poured into the holes. Steel rods are inserted into blocks at 1-1.5m distance as the building height is G+4. The masonry wall becomes reinforced wall structure which increase the cost of construction.	1st course upon DCP using cement mortar and rest course dry stacked. No cement slurry or reinforcement required.
Plastering	Plastering with cement in interior and exterior of walls, column, beam, slab.	No plastering required except in door and window openings and column, beam and slab joints.	No plastering required
Painting	Putty work over plastering and distempering and painting is done.	No putty, distumping, painting. Water proof painting is done above pointing work of IB block grooves.	No painting required. Water proofing painting is done to avoid dampness.
Lintel/Sill Beam	RCC Lintel beam cast at required height.	Lintel beam is concealed among IB as the beam is cast using U-block with reinforcement and concrete.	Lintel beam and sill beam using U-block with reinforcement and cement concrete.
Flooring	Flooring made using tiles and other materials	Flooring made using tiles and other materials	Flooring made using tiles and other materials
Electrical & Plumbing conduit	After block work is completed, chasing is done and conduit pipes are laid and concealed using plastering/	The conduit work is done in parallel with the block work as the conduit are inserted into the IB and metal box are placed along with IB at required and pre-designed locations. The conduit is concealed and no chasing needed.	The conduit work is done in parallel with the block work as the conduit are inserted into the IB and metal box are placed along with IB at required and pre-designed locations. The conduit is concealed and no chasing needed.

3.2 RESIDENCE OF RAJESH, CHENNAI

PROJECT DETAILS	
Client	Mr. Rajesh
Location	Exotic villas, Agaram road, Salaiyur, Chennai, Tamilnadu
Interlocking Block Manufacturer	BGMR & Co Interlocking Blocks, Muttukadu, Chennai
Interlocking Block Name	Cement Solid Interlocking Block
Block Size	12" x 8" x 5" / 12" x 6" x 5" (300mm x 200mm x 130mm) (300mm x 150mm x 130mm)
Building Type	Residence
No. of Floors	Single Storey
Site Area	2400 sqft

Floor Area	926.00 sqft
Structure Type	Framed Structure with Interlock Block Masonry wall
Slab Type	RCC Slab
Sub-Structure	Isolated Footing with pillar and earth beam.
Project Start	22.02.2021

3.2.1 Specification of Solid Cement Interlocking Block

- a) Material: Fine dust (P grade M-sand), 6mm course aggregate, OPC mix.
- b) Production: Machine made, Compressed using Hydraulic Press
- c) Finish: Surface has smooth finish and borders are straight. Edges are bevelled and sharp
- d) Interlocking Type: Dry Interlocking (No mortar between brick courses), Interlocking in both direction
- e) Colour: Cement gray colour
- f) Size: LxWxH (300x200/150x130mm)
- g) Compression Strength: 6.3-6.6Mpa
- h) Water absorption: 8% by weight
- i) Max Variation: 5mm
- j) Loading: Suitable for both load bearing and non-load bearing



Fig 3.21 Solid Cement Interlocking Block

3.2.2 Need for Interlocking Block in Project:

- a) Client needed low cost construction option
- b) Needed traditional look and feel to the project - warm and cosy

c) Quick construction

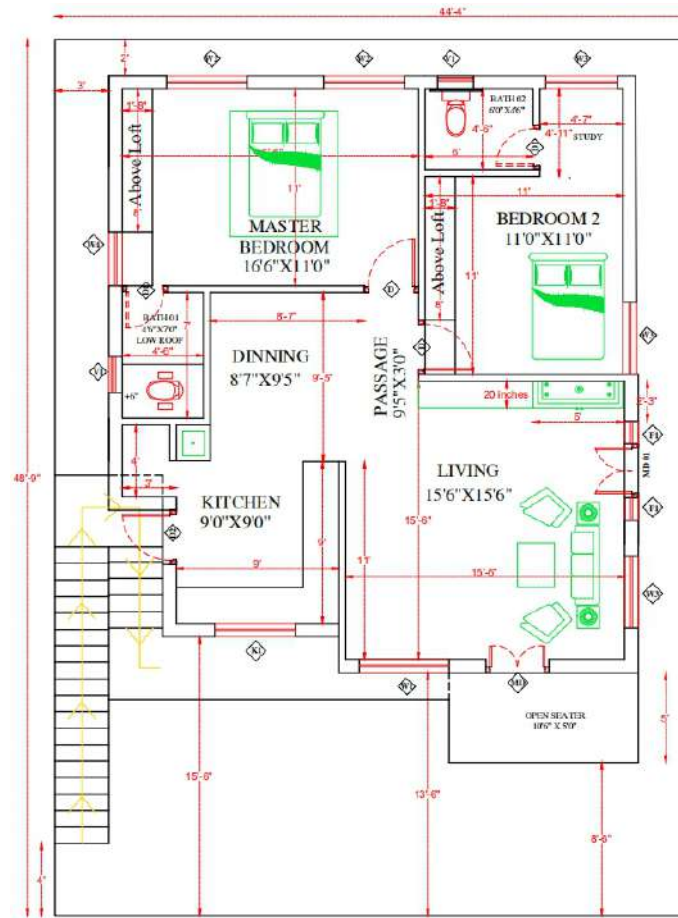


Fig 3.22 Floor Plan of Residence of Rajesh, Chennai

3.2.3. Construction Technique

In the study, the masonry techniques used in the project are studied.

3.2.3.1. Sub Structure:

Foundation is conventional isolated RCC foundation. The plinth beam is at 6" above existing ground level as interlocking blocks can not be trusted to be used for underground construction. Above plinth beam, the basement wall is constructed using interlocking block.



Fig 3.23 Construction Technique - Basement Block Work

3.2.3.2. Damp proof course:

The DCP has to be laid before starting the 1st course of the interlocking block. It is laid upon basement wall structure.



Fig 3.24 Construction Technique - DPC

3.2.3.3. First course of Masonry system

The 1st course of interlocking block use minimum cement mortar to bind the blocks together. Proper care is taken to ensure correct alignment of course as error in 1st course can lead to vital problems.

3.2.3.4. Other course of Masonry System

The rest of the courses are laid one above the other in dry stacking manner without using cement mortar or slurry. At each course, the alignment is checked and the surface is cleaned before laying other course. The process is quick and easy. A Metal strip bar is inserted into the block in the ends at every 2-3 course to ensure settlement, lock-age of block in its place and wall interconnection.



Fig 3.25 Construction Technique - Block Arrangement

3.2.3.5. Lintel & Sill Beam

The lintel beam is cut lintel placed upon openings only. Continuous lintel is used in walls which are not connected from column to column but to other walls. Sill beam is also laid to avoid crack and even sill.

3.2.3.6. Column casting:

The RCC columns are cast after the wall works are completed upto lintel level. The column are made such that the bonding between the wall blocks and column is stronger and more permanent as the concrete gets stuck to the walls during casting making the walls stable.

3.2.3.7. Beam and Slab:

The RCC beam and slab are cast in conventional manner with greased metal scuffholding. The gap between the interlocking block wall and the beam bottom is filled with lean concrete to level the interlocking block head groove.

3.2.3.8. Wall Finishing

The interlocking block walls are finished with pointing by cement paste and brushed with cement watery paste. The grooves is done upon the cement paste. The walls is painted with water proofing cement paint later. No putty, plastering, distemper is provided.



Fig 3.26 Construction Technique - Wall Finishing

3.2.3.9. Plastering

Plastering is done for column, beam and opening of wall and window only.

3.2.3.10. Window and Door

The door are made of 2nd class teak woor and windows are made of UPVC.

3.2.3.11. Flooring

The flooring are vetrified flooring and ceramic flooring with ceramic dados in toilet and kitchen. Skirting is provided at all area.

3.2.3.12. Electrical and Plumbing

The conduit for electrical and plumbing are laid through chasing and cutting the blocks and laying conduit/ The conduit are closed using plastering and pointing is done to match its patten with surrounding blocks.

3.2.3.13. Connecting 200mm wall and 150mm wall

The walls are connected using MS strip.plate which is inserted into block and kept in plate using cement paste. The MS strip is 6 inch long, with 3 inch inserted into one wall in between block at every 3rd course and remaining 3 inch is inserted into the other wall.

3.2.4 Cycle Time for Laying Interlocking Block

Table 3.3 Cycle Time Analysis

No	Task	Description	Time	Assumption & Comments
1.	Fetch	Retrieve unit from cube	4 sec	The unit is placed within 10' proximity to the labour
2.	Lift	Pick up unit	2 sec	Using established OSHA Standards
3.	Return	Go back to the wall	4 sec	The unit is placed within 10' proximity to the labour
4.	Inspect	Look over block	2 sec	Examine for imperfection
5.	Check	Check surface for debris	3 sec	Quick visual look at bed joint
6.	Clean	Remove debris	2 sec	This is rarely the case
7.	Lay	Place block on the wall	2 sec	Ensure proper orientation
8.	Seat	Rock to secure	2 sec	Reducing the possibility of point loading
Per cycle time in seconds			21	

3.2.5 Detail Drawing

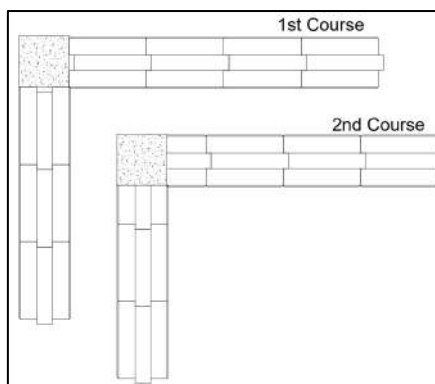


Fig 3.27 Interlocking Block - course Arrangement

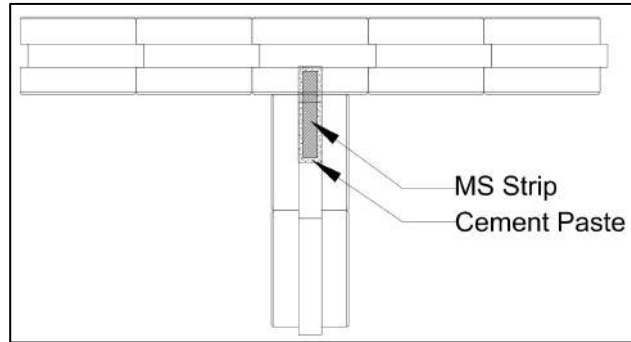


Fig 3.28 Interlocking Block Wall Connections

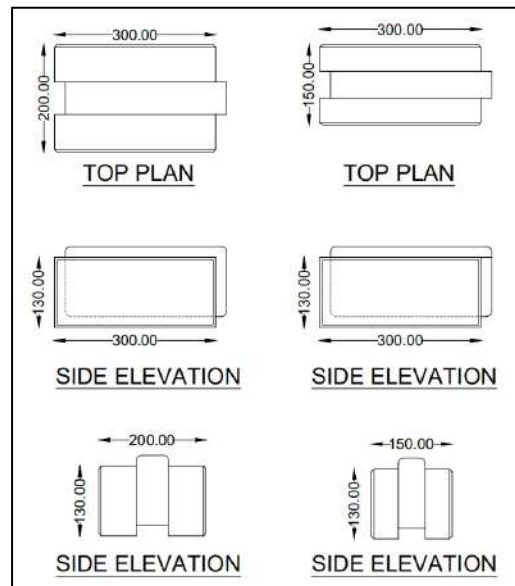


Fig 3.29 Interlocking Block Unit Types

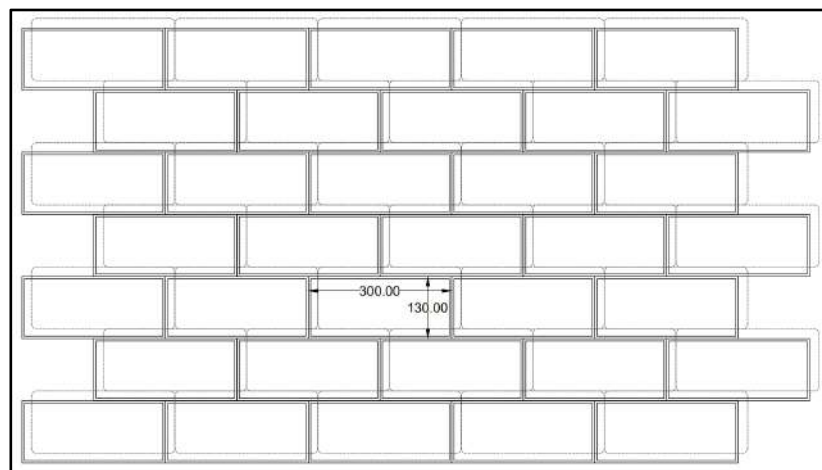


Fig 3.30 Interlocking Block Wall Elevation

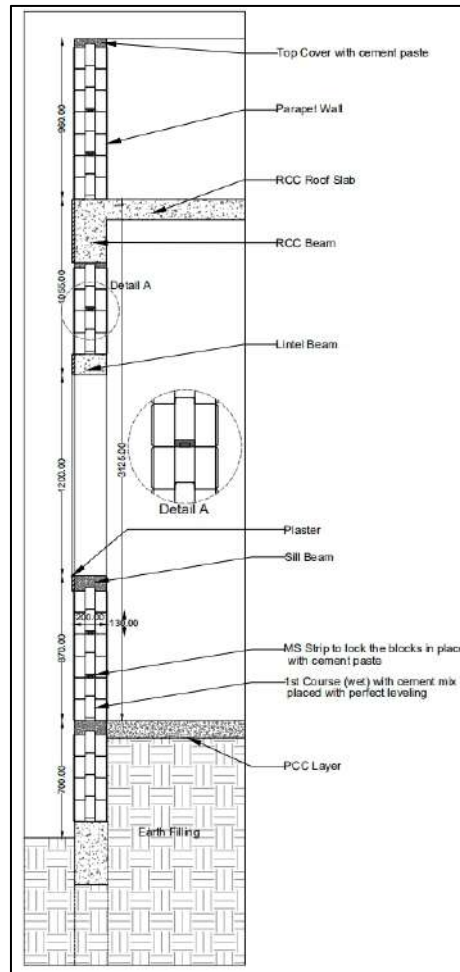


Fig 3.31 Interlocking Block Wall Section Details

3.2.6 Labour and Material Cost Analysis

Description	Quantity	Rate	Amount
Labour cost per m³ for Brick			
Mason (brick layer) 1st class	0.47 day	₹ 900	₹ 423
Mason (brick layer) 2nd class	0.47 day	₹ 850	₹ 399.5
Coolie	1.8 day	₹ 600	₹ 1080.00
Bhisti	0.2 day	₹ 600	₹ 120
Total Labour cost per m³ for brick			₹ 2022.50
<i>Note: Referred from DAR (Civil), 2018. Labour rate is taken as per market rate in Chennai</i>			

Description	Quantity	Rate	Amount
Labour cost per m³ for Interlocking Block (CSEB)			
Mason (brick layer) 1st class	0	₹ 900	0
Mason (brick layer) 2nd class	0	₹ 850	0
Coolie	0.4 day	₹ 600	₹ 240.00
Bhisti	0	₹ 600	0
Total Labour cost per m³ for brick			₹ 240.00
<i>Note: Referred from DAR (Civil), 2018. Labour rate is taken as per market rate in Chennai</i>			

Masonry System	Material Cost per m³	Labour Cost per m³	Total Cost per m³
Brick	₹ 5222.21	₹ 2022.50	₹ 7244.71
Interlocking Block (CSEB)	₹ 4672.84	₹ 240.00	₹ 4912.84

Items	IB Wall	Brick Wall
Price Per Unit	₹ 33.00	₹ 8.00
Amount of units per m³	129 nos	494 nos
Labour per m³	₹ 240.00	₹ 2022.50
Cement mortar (1:6) per m³	-	0.25 cum

Description	Quantity	Rate	Amount	Description	Quantity	Rate	Amount
Material cost per m³ for Brick				Material cost per m³ for Interlocking Block (CSEB)			
Brick Units	494 units	₹ 8.00	₹ 3952.00	Brick Units	129 units	₹ 33.00	₹ 4257.00
Cement mortar 1 : 6	0.25 cum	₹ 3217.50	₹ 804.37	Cement mortar 1 : 6	0	₹ 3217.50	0
Scaffolding	1.13 day	₹ 368.00	₹ 415.84	Scaffolding	1.13 day	₹ 368.00	₹ 415.84
Water	-	-	₹ 50.00	Water	0	0	0
Total Material cost per m³ for brick			₹ 5222.21	Total Material cost per m³ for brick			₹ 4672.84
<i>Note: Referred from DAR (Civil), 2018. Material rate is taken as per market rate in Chennai and DAR rates</i>				<i>Note: Referred from DAR (Civil), 2018. Material rate is taken as per market rate in Chennai and DAR rates. The IB is assumed to be dry stacked.</i>			

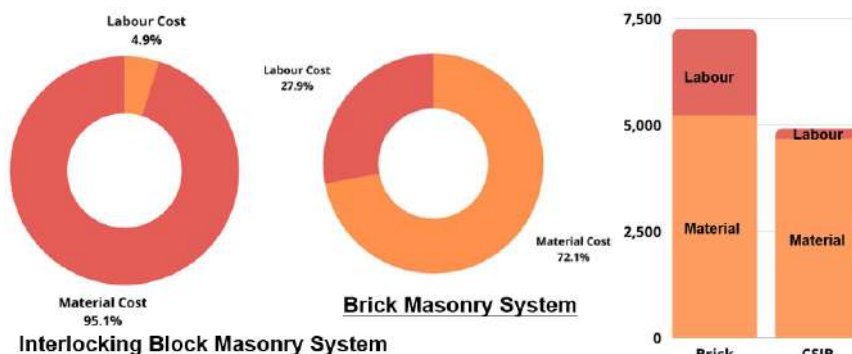


Fig 3.32 Interlocking Block vs Brick Masonry System

Table 3.4 Construction Cost Analysis

Sl. No	Activities	Conventional Construction using brick	Interlocking Block Construction	Remarks
1.	Foundation and Plinth Works	₹ 4,68,554.51	₹ 4,10,556.20	The foundation is conventional forundation and the basement block work is made with IB dry stacking
2.	RCC Works - Super Structure	₹ 3,71,067.85	₹ 3,71,067.85	The super structure is column, slab and beam framework with cut lintel.
3.	Masonry Works	₹ 1,85,367.11	₹ 1,19,431.86	The blockwork is IB with 1st course using wet mortar and M5 strip in every 2 course
4.	Plastering	₹ 1,65,806.06	₹ 11,807.04	No plastering except in beam and column.
5.	Painting	₹ 1,15,946.39	₹ 96,140.59	Water proofing paint only. No putty work. Pointing work done using cement paste
6.	Flooring	₹ 2,17,875.88	₹ 2,17,875.88	The flooring shall be same
7.	Door and Windows	₹ 1,55,905.37	₹ 1,55,905.37	The doors and windows shall be same
8.	Steel Works	₹ 47,160.00	₹ 47,160.00	The steel works shall be the same
9.	MEP Works - Plumbing	₹ 1,72,768.32	₹ 1,42,994.48	10% of the civil work
10.	MEP Work - Electrical	₹ 1,72,768.32	₹ 1,42,994.48	10% of the civil work
TOTAL COST OF CONSTRUCTION		₹ 20,73,219.80	₹ 17,15,933.75	The cost of construction is low for IB system compared to brick in low rise building due to reduced plastering and painting and labour savings.
COST PER SQFT		₹ 2238.89/sqft	₹1853.06/sqft	

Note: The cost is not inclusive of OHT, UGS, compound wall, lift and other additional works

3.2.7 Project Schedule of Interlocking Block

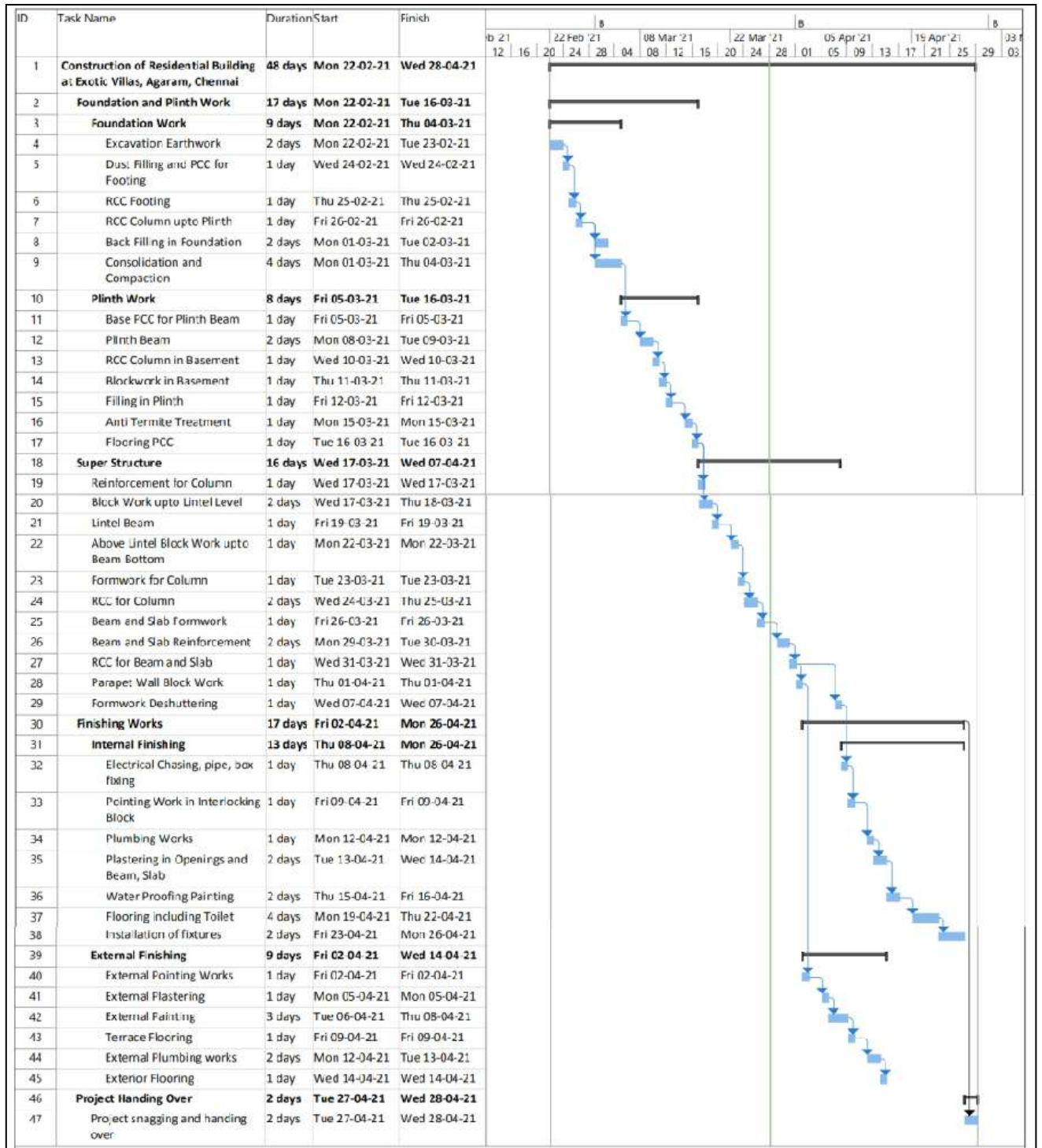


Fig 3.33 Project Schedule Programme

3.2.7 Labour Productivity Analysis

■ Total Duration for Masonry work of super structure:	2 days
■ No. of working hour :	2 days x 8 hour = 16 hour
■ Total quantity of Masonry work:	25.40 cum
■ No of units used :	3280 nos
■ No. of Team working in masonry work :	2 team (2 labour in each team)
■ No. of units arranged per hour :	3280 nos / (16 hr x 2 team) =102.5 units / hour / team

3.2.8 Equipment Required for Construction

- a) Mason Trowel
- b) Bricklayer's Hammer
- c) Joint Filler
- d) Square Trowel
- e) Plumb Bob
- f) Right angled Scale
- g) 2ft spirit level
- h) Angle grinder
- i) Cut-off machine to cut the blocks
- j) Rubber Hammer to adjust the blocks
- k) Brush

CHAPTER 4

PRIMARY DATA COLLECTION

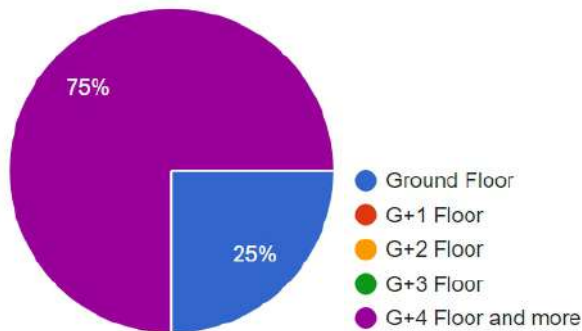
4.1 DATA COLLECTION THROUGH QUESTIONNAIRE:

A survey is conducted to gather data about interlocking block construction. The sample group for answering the questionnaire are selected through their experience with interlocking block.

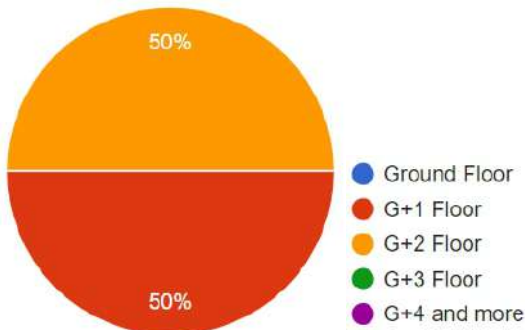
The participants are chosen from south India, who work with interlocking block and are interlocking block manufacturers. The questionnaire is sent to 7 participants and received valued response from them. The selected participants were Architect, civil engineer, IB manufacturer, contractor.

The questions asked and response received are recorded and analysed.

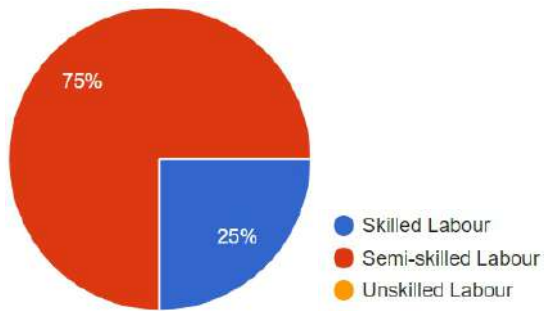
A. Maximum no. of storey interlocking block can be used for in framed structure.



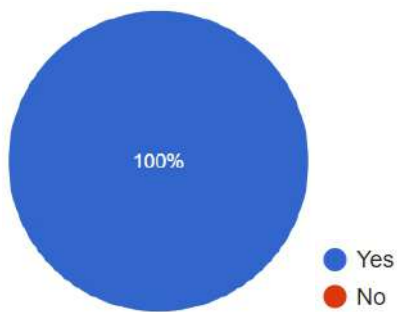
B. Maximum no. of storey interlocking block can be used for in load bearing structure.



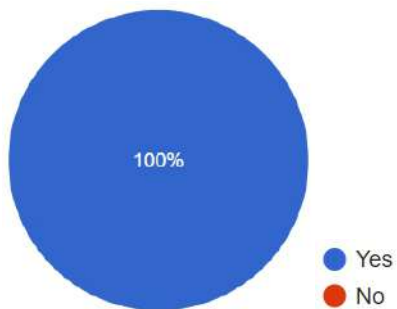
C. Type of labour required for Interlocking Block.



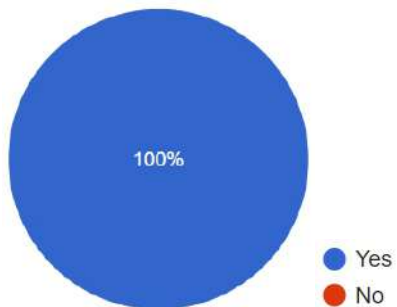
D. Is interlocking block better than Brick.



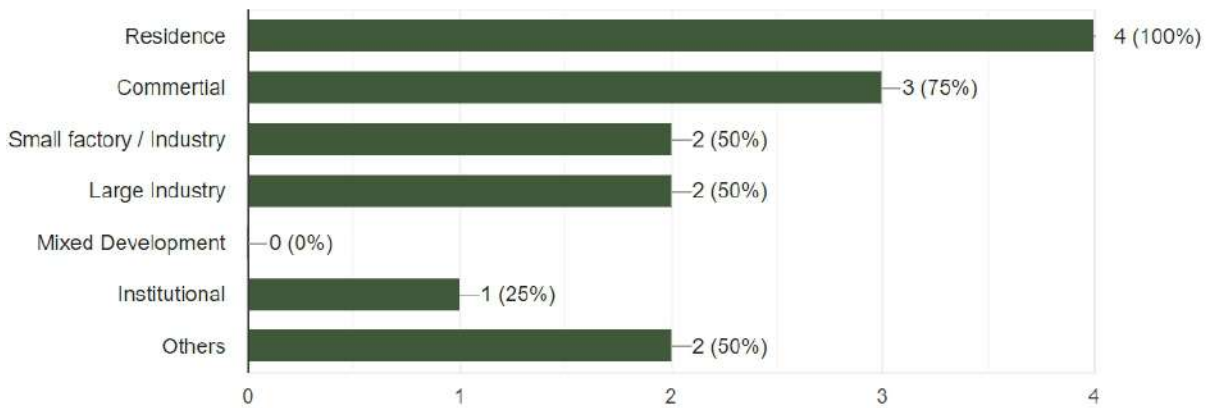
E. Does interlocking block reduce water consumption in construction.



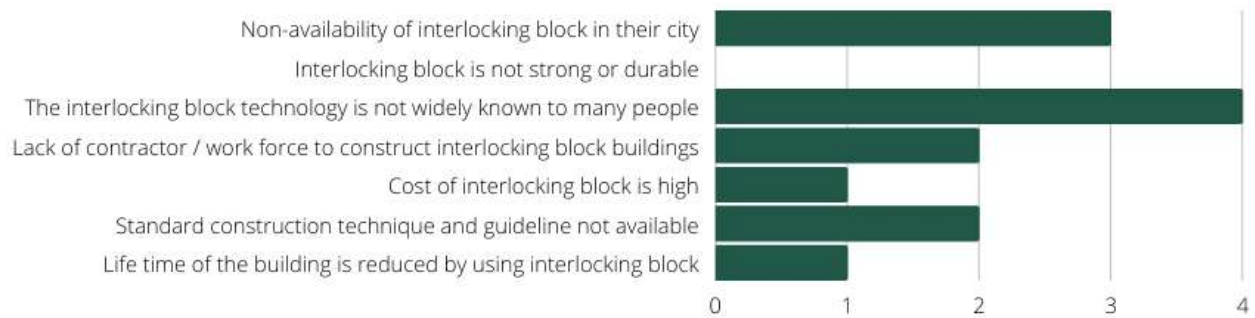
F. Does interlocking block reduce no. of labour required.



G. Type of projects using Interlocking Block



H. Why interlocking block construction is slow and still not widely used in South India



CHAPTER 5

ANALYSIS AND RESULTS

5.1 LIVE CASE STUDY - COMPARISON

Table 5.1 Comparison Summery

Properties		Case Study - 1	Case Study - 2	Conventional Brick Masonry
1.	Block Type	Compressed Stabilised Earth Blocks - Hollow interlocking block	Cement Solid Interlocking Block	Red Clay Brick
Block Properties				
2.	Block Size	300mm x 150mm x 90mm	300mm x 200/150mm x 130mm	230mm x 110mm x 70mm
3.	Strength of Block	12 Mpa	6.3 - 6.6 MPa	3.5 MPa - 15 MPa
4.	Water Absorption	5-8%	8%	less than 15%
5.	Raw Material	soil block stabilized with cement (6-8% cement)	Fine dust (P grade M-sand), 6mm course aggregate, OPC)	Soil, sand
Construction Properties				
6.	Maximum Height of Building	G+4	G+2	G+4 & More
7.	Type of structural system preferred	Framed Structure	Framed Structure	Load Bearing / Framed Structure
8.	Internal masonry Reinforcement	Yes	No	No
Productivity Analysis				
9.	Cycle Time	24 seconds	21 seconds	-
10.	Labour		102.5 units per	60 units per

	Productivity		hour per team	hour per team
Cost Analysis				
11.	No. of units per cum	247 nos	129 nos	494 nos
12.	Material Cost per cum	₹ 7825.84	₹ 4672.84	₹ 5222.21
13.	Labour Cost per cum	₹ 435.00	₹ 270.00	₹ 2022.50
14.	Cost of 1 Block	₹ 30.00	₹ 33.00	₹ 8.00
Design for Deconstruction Potential				
15.	Rating of DFD Potential	4.88 / 7	5.50 / 7	-

5.2 CONSTRUCTION OF MASONRY WALL ANALYSIS

Table 5.2 Analysis of Wall Construction using types of IB Blocks

Details	Compressed Stabilised Earth Hollow interlocking block	Cement Solid Interlocking Block
Wall Size	3m (h) x 3m (l) x 0.15m (t)	3m (h) x 3m (l) x 0.20m (t)
No. of Block Used	330 blocks	230 blocks
Block per course	10 blocks	10 blocks
No of course	33 course	23 course
Cycle time per block	24 seconds	21 seconds
Time analysis for construction of full wall	260 Minutes (3hr 16 minutes)	144 Minutes (2 hr 24 minutes)

Wall Finish		
Construction Team	Semi Skilled Worker - 1 nos Unskilled Worker - 1 nos	Semi Skilled Worker - 1 nos Unskilled Worker - 1 nos
Cost for construction	Rs. 11,152.13	Rs. 8,843.11

5.3 UNIT COST OF INTERLOCKING BLOCK - COST ANALYSIS

Compressed Stabilised Earth Hollow interlocking block			
Material	Soil	94%	
	Cement stabilizer	6%	
Cost Breakup	Labour	20-25%	
	Equipment	3-5%	

Compressed Stabilised Earth Hollow interlocking block				
Material	Quantity	Unit	Rate	Amount
Sand	5.26 (64%)	kg	Rs. 1.91	Rs 10.04
Laterite	2.26 (30%)	kg	Rs. 1.40	Rs. 3.16
Cement	0.48 (6%)	kg	Rs. 8.00	Rs. 3.84
TOTAL MATERIAL COST				Rs. 17.04
ADD LABOUR COST PER UNIT (20%)				Rs. 3.40
ADD EQUIPMENT COST PER UNIT (5%)				Rs. 0.85
TOTAL COST OF UNIT BLOCK				Rs. 21.29

Stabilised Earth Hollow Interlocking Block				
Stabilised Earth Hollow Interlocking Block	Market Rate	Production Rate		
	Rs. 30.00	Rs. 21.29		

Solid Cement interlocking block		
Material	P-grade M-Sand	24%
	6mm course aggregate	60%
	OPC Cement	16%
Cost Breakup	Labour	20-25%
	Equipment	3-5%

Solid Cement interlocking block				
Material	Quantity	Unit	Rate	Amount
M-Sand	2.4 (24%)	kg	Rs. 1.50	Rs 3.60
Aggregate	6.0 (60%)	kg	Rs. 0.3	Rs. 1.80
OPC	1.6 (16%)	kg	Rs. 9.0	Rs. 14.4
TOTAL MATERIAL COST				Rs. 19.80
ADD LABOUR COST PER UNIT (20%)				Rs. 3.96
ADD EQUIPMENT COST PER UNIT (5%)				Rs. 0.99
TOTAL COST OF UNIT BLOCK				Rs. 24.75

Solid Cement Interlocking Block		
Solid Cement Interlocking Block	Market Rate	Production Rate
	Rs. 33.00	Rs. 24.75

5.3 DECONSTRUCTION POTENTIAL OF INTERLOCKING BLOCK

Table 5.3 Rating Deconstruction Potentials of Interlocking Blocks

SL NO	DESIGN FOR DECONSTRUCTION PRINCIPLES & STRATEGIES	STABILISED HOLLOW EARTH INTERLOCKING BLOCK	SOLID CEMENT INTERLOCKING BLOCK
1.	Use high-quality reused materials that encourage for the reclamation of materials.	1 2 3 4 5 6 7	1 2 3 4 5 6 7
2.	Minimize the different types of materials to reduce complex separation processes.	1 2 3 4 5 6 7	1 2 3 4 5 6 7
3.	Avoid toxic and hazardous materials	1 2 3 4 5 6 7	1 2 3 4 5 6 7
4.	Avoid secondary finishes to materials which making it difficult to find the connections.	1 2 3 4 5 6 7	1 2 3 4 5 6 7
5.	Separate non-structural de-construction from structural de-construction.	1 2 3 4 5 6 7	1 2 3 4 5 6 7
6.	Minimize number of fasteners and connectors to increase speed of disassembly.	1 2 3 4 5 6 7	1 2 3 4 5 6 7
7.	Design joints and connectors to withstand repeated assembly and disassembly..	1 2 3 4 5 6 7	1 2 3 4 5 6 7
8.	Allow for parallel disassembly to decrease the time on-site during deconstruction.	1 2 3 4 5 6 7	1 2 3 4 5 6 7
9.	Use lightweight materials that are readily handled by labor or smaller equipment	1 2 3 4 5 6 7	1 2 3 4 5 6 7
10.	Use of wide structural grid as possible to maximize the non-structural wall elements.	1 2 3 4 5 6 7	1 2 3 4 5 6 7
11.	Consolidate MEP systems to minimize runs and hence unnecessary entanglement.	1 2 3 4 5 6 7	1 2 3 4 5 6 7
12.	Make sure stability is maintained during deconstruction	1 2 3 4 5 6 7	1 2 3 4 5 6 7
13.	Ensure access to building components for deconstruction.	1 2 3 4 5 6 7	1 2 3 4 5 6 7
14.	Deconstruction should be possible with common tools and equipment	1 2 3 4 5 6 7	1 2 3 4 5 6 7
15.	Construction drawings, materials and components, Structural properties - details	1 2 3 4 5 6 7	1 2 3 4 5 6 7
16.	Material durability shall cater to the reusability	1 2 3 4 5 6 7	1 2 3 4 5 6 7
17.	Easy removal with less skilled labour	1 2 3 4 5 6 7	1 2 3 4 5 6 7
18.	Cost for de-construction is minimal	1 2 3 4 5 6 7	1 2 3 4 5 6 7
		Rating: 4.88 / 7	Rating: 5.50 / 7

5.5 SWOT ANALYSIS OF INTERLOCKING BLOCK

5.5.1 Strength

- Raw material readily available
- Easy to produce with less process
- The product is durable
- Easy to transport to site or make in site
- Used for temporary building structures
- Give aesthetic appearance
- Use local, cheap, less-skilled labour
- Easy construction process
- Time saving construction

5.5.2 Weakness

- a) Not used widely as load bearing structure
- b) Durability not known yet
- c) Damage during transport in grooves
- d) Dampness into building if not constructed properly
- e) Not yet suitable for sub-structure construction
- f) Not recommended for high rise building
- g) Not recognised by Gov. of Tamil Nadu

5.5.3 Opportunity

- a) Various mix of raw materials and proportion of material to create new stronger and durable IB
- b) Availability of number of production units
- c) Increase production capacity
- d) Need for new masonry technology to replace brick
- e) Need for water-less construction
- f) Need for labour efficient construction
- g) Need for quick construction
- h) Need for Resource efficient construction
- i) Lack of technical knowledge

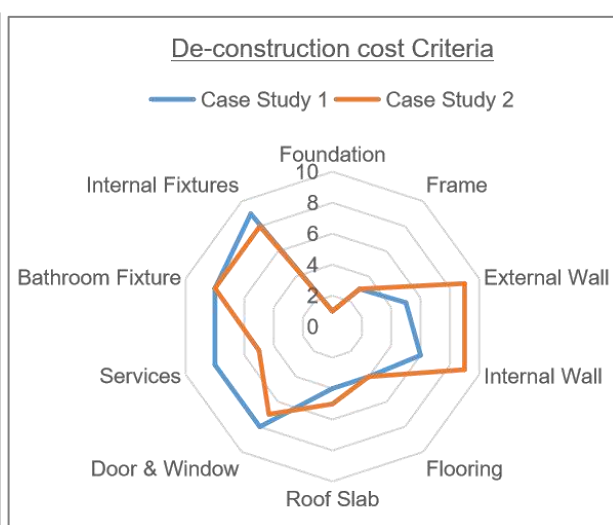
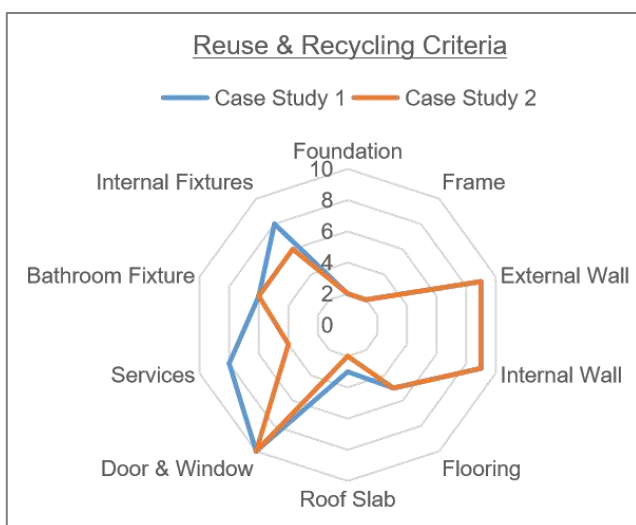
5.5.4 Threats

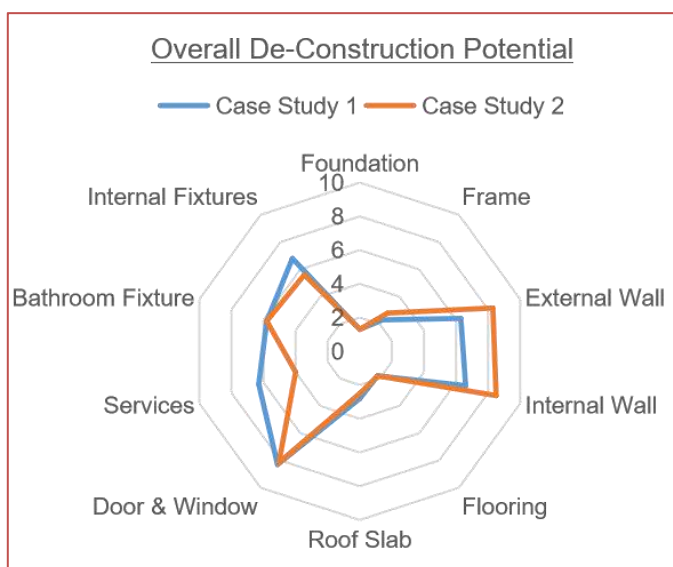
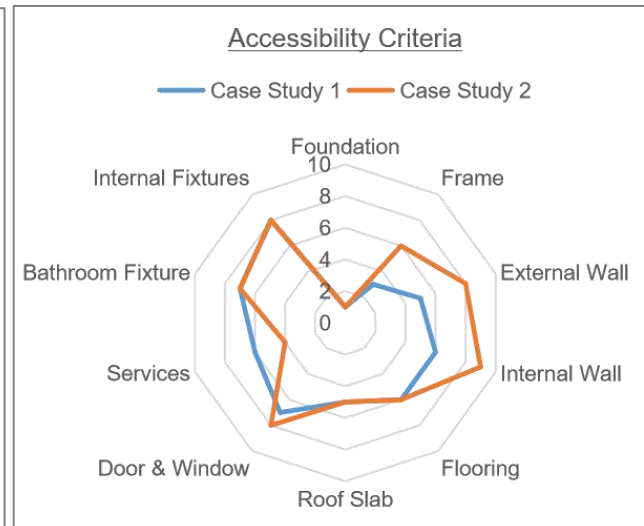
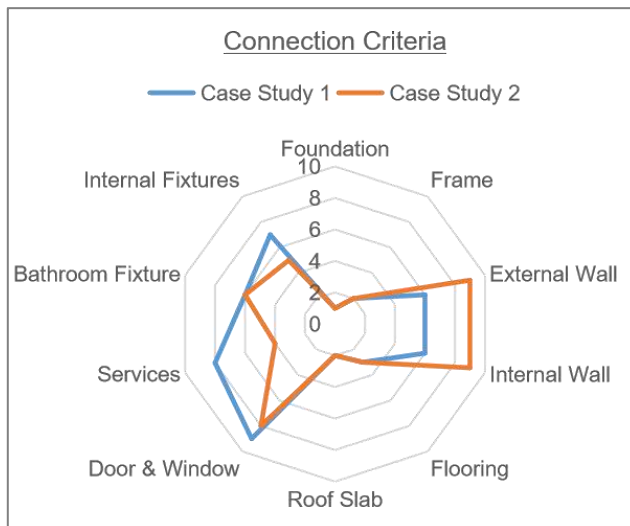
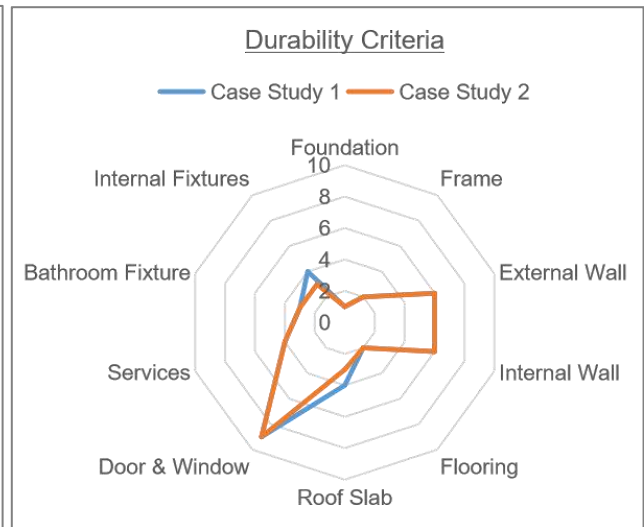
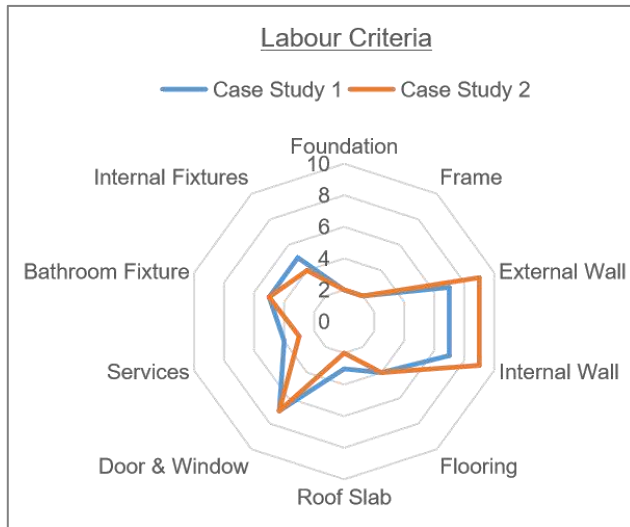
- a) Face competition from other building material
- b) Lack of knowledge in construction technique and improper construction
- c) Wrong Construction Methods
- d) Misconception about Interlocking Block among people

5.6 DECONSTRUCTION CRITERIA OF IB CASE STUDIES - DE-CONSTRUCTION POTENTIAL

Table 5.4 Building Elements of Case Study

ELEMENT	CASE STUDY 1	CASE STUDY 2
Frame	RCC framed structure	RCC framed structure
Foundation	Isolated foundation	Isolated foundation
External Wall	Hollow stabilised compressed mud interlocking block	solid cement interlocking block
Floor/ceiling	Shallow clay pot filler slab	RCC Slab
External Finish	Exposed interlocking block with water proofing paint	Exposed interlocking block with water proofing paint
Floor Finish	Ceramic , Vetrified tiles	Ceramic , Vetrified tiles
Window, door	UPVC Window/door, Wooden door	UPVC windor, wooden door
Services	Plumbing, electrical, split air conditioning	Plumbing, electrical, split air conditioning
Fittings and fixture	modular kitchen, modular interior shelves	RCC kitchen counter, modular shelf





Inference

As per the spider graph, the building using hollow interlocking block is less possible for de-construction as it is applied in G+4 building and the IBs had to be reinforced. The walls were difficult to be removed. But in hollow IB, the services can be removed easily.

In solid IB, the walls are removed easily as they are dry stacked in single storey building. But the service are difficult to remove as they are chased into the wall and plastered.

DE-CONSTRUCTION POTENTIAL OF INTERLOCKING BLOCK			
Elements	Case Study 1	Case Study 2	Suggestion & Recommendations
Foundation	13%	13%	The foundation is not designed to be deconstructed. The material used can be reclaimed after demolition such as debries and reinforcement rods.
Frame	23%	28%	The RCC column, beam can be replaced with hollow interlocking block for column and U-block for beam. The frame can be created using interlocking block with reinforcement.
External Wall	63%	83%	The solid IB shall be used for load bearing walls. The hollow IB shall be used for non-load bearing walls IB shall be used for G+2 structure only to avoid reinforcing walls and concreting the blocks.
Internal Wall	66%	85%	The internal walls shall not be bonded with cement. They shall be dry stacked.
Flooring	18%	18%	The ceramic tiles are easy to remove than vetrified tile Vinyl Flooring is suggested as they can be removed easily. Use of tools to cut through grout.
Roof Slab	28%	25%	Light weight slabs such as deck slab, panel slab, pre-fab slab can be used.
Door & Window	83%	81.6%	The doors and windows can be removed easily through screw connection. The material can be made of reusable, salvageable material. They can be screwed to lintel and sill u-block
Services	63%	40%	The hollow IB can be used to electrical and plumbing

			conducting. Special conduit block can be made for laying pipes They shall be accessible and separate from masonry system.
Bathroom Fixture	58%	58%	The CP fixtures and fittings are made removable by using bolt and nut/ screw connections.
Internal Fixture	68%	56%	The furniture, interior works are modular and removable. Kitchen, shelves, wardrobe shall be modular.

5.7 FESABILITY ANALYSIS OF INTERLOCKING BLOCK AS DESIGN FOR DECONSTRUCTION

PROJECT DETAILS	
Client	Mr. Umar Farook
Location	Sithalapakkam, Chennai, TN
Building Type	Mixed use
Site Area	2095.90 sqft
Floor Area	1281.01 sqft
Building Height	Single Storey
Architect	Ar.Swathi
Stage 1	1BHK House + office
Stage 2	2 BHK House

To understand the feasibility and efficiency of using interlocking block masonry system for design for deconstruction principal. The project chosen to analyse this is a residence of Mr. Umar Farook who has chosen to build his house to develop into two stages as his family shall grow through years. He initially want the house to be single bedroom home which can be later converted to two bedroom house for his future kids.

Architect was chosen and plan was framed to make the house into a flexible housing with removable wall system. The material chosen for the flexible wall is interlocking block. The entire construction technique was framed to suit to easy de-construction of wall and re-construction of the wall at other location with minimum wastage and cost.

The residence is designed to be flexible and cater to the need of the user. The user is couple who need their house to be adaptable such that after 3 to 5 years, the house can be modified to the growing family.

The interlocking blocks were used for walls and the plumbing lines are made to be removable. The toilet fixtures and fittings are removable. Measures are taken to make the elements suitable for deconstruction.

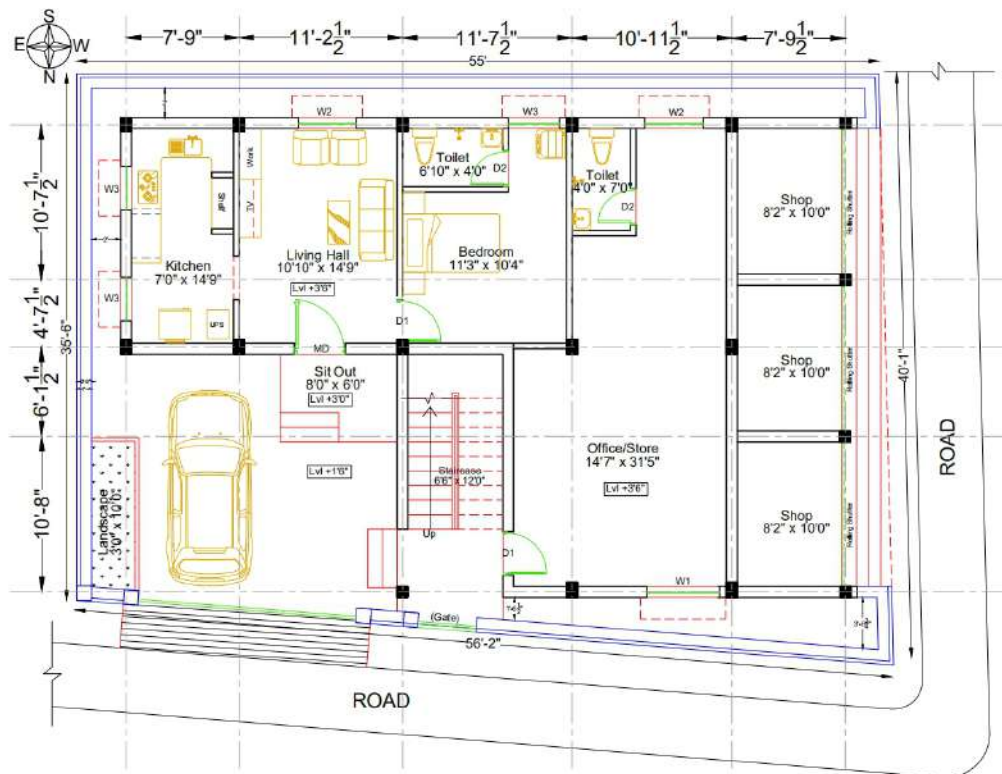


Fig 5.1 Stage 1 - Ground Floor Plan



Fig 5.2 Stage 2 - Ground Floor Plan

Stage - 1= 1BHK + Office, Residence Area - 501.50 sqft, Office Floor Area - 432.14 sqft

Stage - 2 = 2BHK, Residence Area - 933.64 sqft



Fig 5.3 Walls to be de-constructed and re-constructed

5.7.1 Measures Taken for Flexible Housing Design

Sl. No	Elements	Design Details & Measures Taken for De-Construction
1.	Walls	The wall is made of Hollow Interlocking earth block. The hollow interlocking block is dry stacked.
2.	Finishing	The water proof painting is done on the erected wall. The pointing is done using cement/mud paste in minimal. The Wall surface of the toilet is finished with epoxy paint instead to tile dados.
3.	Lintel	The U-Block is used for lintel. The lintel is provided in opening only. The lintel is provided at height of 2.1m
4.	Flooring	The flooring used is ceramic flooring. The tiles are laid using cement grout, not using chemicals.
5.	MEP Services	The plumbing pipe and electrical conduit is laid into the interlocking block holes. The walls and conduits are erected simuntanisouly but separate from masonry system. The MEP services are pre-designed to not be laid in to-be-deconstructed walls. The fixtures and fittings are removable. The WC is wall mount with provision on external wall for soil pipe . The lights are LED ceiling mount. No light points on removable walls. The drain pipe for AC units are also laid into interlocking blocks. The floor drain used for the toilet is side drain which is connecte d to external wall through provision for outlet.

6.	Window & Door	The windows and doors are UPVC. The doors of bedroom and toilet can be removed and placed in new location by removal of screws from plaster of the openings. The door and wall connection is screw joints which is easy removable. The number of doors and windows remain same to avoid procurement of new material.
7.	Sub-Structure & Frame	The sub-structure undergoes no changes during stage - 2 construction. The plinth beam is pre-laid as per the stage-2 requirement. There is no change in column and beam arrangement.
8.	Roof	The roof is made of RCC.

5.7.2 Feasibility Analysis for Flexible Housing Design

5.7.2.1 Material Efficiency

STAGE - 1

The no. of units used for stage 1 - removable walls:

$$\text{Wall-1} = 4.50 \times 0.15 \times 2.70 = 1.822 \text{ cum}$$

$$\text{Wall-2} = 2.08 \times 0.15 \times 2.70 = 0.842 \text{ cum}$$

$$\text{Wall-3} = 1.21 \times 0.15 \times 2.70 = 0.490 \text{ cum}$$

$$\text{Wall-4} = 0.90 \times 0.15 \times 2.70 = 0.364 \text{ cum}$$

Total removable wall volume = 3.518 cum

Less door portion = 3.518 cum - 0.519 cum = 2.999 cum

No. of interlocking block used = 741 blocks

STAGE - 2

The no. of units to be used in stage - 2 re-constructed walls:

$$\text{Wall-a} = 3.22 \times 0.15 \times 2.70 = 1.304 \text{ cum}$$

$$\text{Wall-b} = 5.10 \times 0.15 \times 2.70 = 2.065 \text{ cum}$$

$$\text{Wall-c} = 1.22 \times 0.15 \times 2.70 = 0.494 \text{ cum}$$

Total removable wall volume = 3.863 cum

Less door portion = 3.863 cum - 0.897 cum = 2.966 cum

No. of interlocking block used = 733 blocks

It can be derived that the interlocking block used in stage 1 will be sufficient to be reused for stage 2. No new procurement is needed. Hence, Material and resource saving is achieved.

5.7.2.2 Cost Efficiency

Interlocking Block - Reconstruction

COST FOR WALL CONSTRUCTION IN STAGE - 2

Interlocking Block material cost = Rs.0.00

Interlocking Block re-construction labour cost = Rs. 2000.00

Interlocking block de-construction cost = Rs. 4000.00

Cement for pointing = Rs. 300 per sqm = 53.95 sqm x Rs.300 = Rs. 16,183.80

Water proofing painting = Rs.100 per sqm = 53.95 sqm x Rs.100 = Rs. 5395.00

Total cost for stage-2 wall construction = Rs.27,578.80

Brick Wall - Reconstruction

COST FOR WALL CONSTRUCTION IN STAGE - 2

Brick material cost = 2.966 cum x Rs.5000 = Rs.14,830.00

Brick re-construction labour cost = Rs. 8000.00

Brick de-construction cost = Rs. 4000.00

Cement for pointing = Rs. 300 per sqm = 53.95 sqm x Rs.300 = Rs. 16,183.80

Water proofing painting = Rs.100 per sqm = 53.95 sqm x Rs.100 = Rs. 5395.00

Total cost for stage-2 wall construction = Rs.48,408.80

Hence, The cost saving achieved through using interlocking block for wall construction is 43%. Also, the construction and demolition waste is nearly zero.

The cost for MEP is also reduced as they can be easily removed and re-done in new location compared to MEP service in brick/solid masonry system.

5.7.2.3 Time Efficiency

The time taken for reconstruction is 4 days in interlocking block which is less compared to 9 days in brick block construction, hence, 55% faster construction.

5.7.3 Responsibility of Stakeholders Involved in Flexible Housing

Design Principles Low Responsibility Medium Responsibility High Responsibility		Owner	Architect	Contractor	Structural Designer	Sub-contractor	Manufacturer	Supplier	Interior Designer	Project Manager
Documentation of De-construction Plan										
Design of Accessible Connection										
Design of modular construction										
Use of bolt & nut/screw/nailed connection										
Separate MEP system										
Design for easy de-construction for labour										
Simplicity of structure and form										
Design for safe de-construction										
Interchangability of structure - flexibility										
Reusability of materials										
Minimise building elements, materials										
Using simple tools and equipments for de-construction										
Separate de-construction and non-de-construction elements										

Fig 5.4 Stakeholder and Their Responsibility

5.7.4 Process of the Flexible Housing Construction

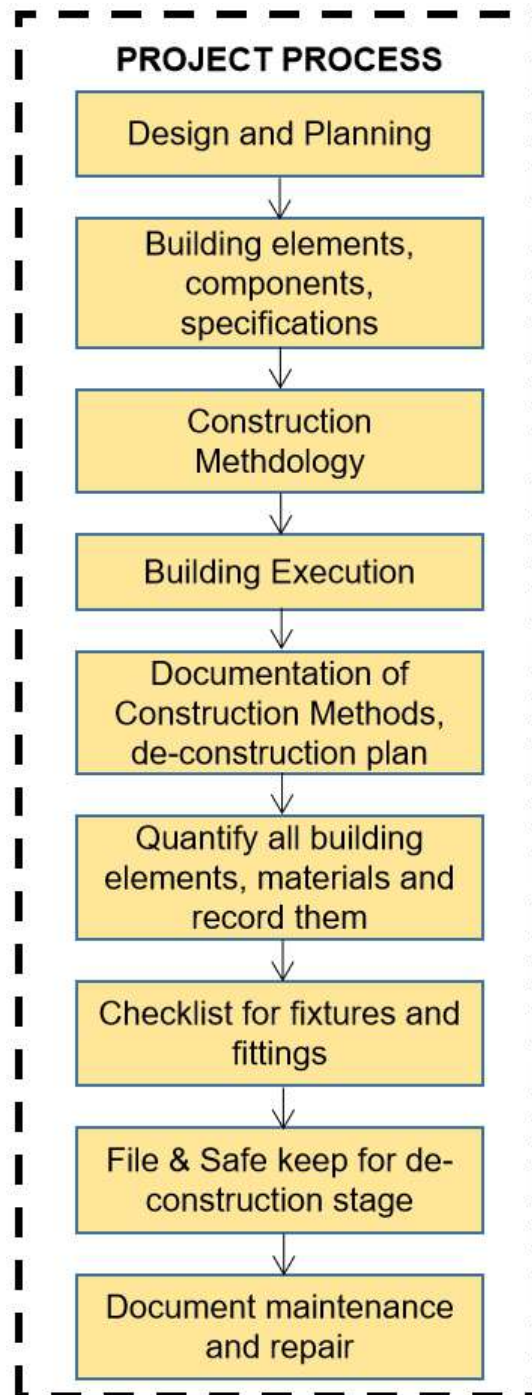


Fig 5.5 Project Execution Process

5.8 CHECKLIST FOR INTERLOCKING BLOCK WORK

1. CHECKLIST FOR MASONRY INTERLOCKING BLOCK WORK					
SL NO	PARTICULARS	STATUS			REMARKS
		YES	NO	NA	
1.	Check availability of materials for a days work and test report				
2.	Clean and brush off work area				
3.	Check for hacking on beam/floor slab				
4.	Make stacking of IB close to work area				
5.	Preparation of cement mortar for 1st course				
6.	Placement of 1st course of IB				
7.	Setting out and check for alignment of block work				
8.	Location of door/window as per arch. dwg is checked				
9.	Holes for reinforcement are made and rods placed in position				
10.	IB are dry stacked and checked for leveling and alignment				
11.	Cement grout are poured into IB and reinforcement slots				
12.	At every intermediate 3 course, MS strip/rod is placed				
13.	Plumb of wall checked				
14.	Grooves of IB checked for alignment and damage				
15.	The electrical and plumbing conduits are laid along with IB				
16.	The electrical and plumbing conduit checked for its location as per drawing				
17.	Metal box are placed and checked for its location				
18.	The interlocking block wall is cleaned				
Project Name:		Building:			Floor:
Checked By:		Room:			Date:
Approved By:		Client:			

2. CHECKLIST FOR LINTEL BEAM USING INTERLOCKING BLOCK					
SL. NO	PARTICULARS	STATUS			REMARKS
		YES	NO	NA	
1.	Check the last course of IB and clear the surface.				
2.	Place the U-block/beam block on lintel height				
3.	Check for leveling and alignment				
4.	Placement of rods of required dia on u-block				
5.	Make right mix of concrete				
6.	Pour concrete and level & compact as per block height				
7.	Check setting of concrete before laying next course				
8.	Check position of lintel on window/door opening as per dwg				
Project Name:		Building:		Floor:	
Checked By:		Room:		Date:	
Approved By:		Client:			

3. CHECKLIST FOR WALL FINISHING					
SL. NO	PARTICULARS	STATUS			REMARKS
		YES	NO	NA	
1.	The grooves are checked alignment and cleaned				
2.	Mix of cement paste is checked with specification				
3.	Pointing is done with appropriate pointing tool				
4.	Check for damages in the IB and correct it				
5.	Check surface of IB wall sprayed with water before pointing				
6.	Check the colour of mortar of pointing				
7.	Check pointing work for neat finish within groove area				
8.	Brush the pointed surface with soft brush after pointing				
Project Name:		Building:		Floor:	
Checked By:		Room:		Date:	
Approved By:		Client:			

4. CHECKLIST FOR PAINTING					
SL. NO	PARTICULARS	STATUS			REMARKS
		YES	NO	NA	
1.	Check the wall for curing of pointing work				
2.	Check the water proofing painting is as per specification				
3.	Check if the colour is as per approved specification				
4.	Check if all the surfaces are clean				
5.	Check if required no. of coats are applied				
6.	Check for paint stains on other non-wall surface and clean them				
7.	Check if painting is applied uniformly				
8.	Check at IB grooves for uniformity				
9.	Check if area is cleaned after work				
Project Name:		Building:		Floor:	
Checked By:		Room:		Date:	
Approved By:		Client:			

5. CHECKLIST FOR PLASTERING					
SL. NO	PARTICULARS	STATUS			REMARKS
		YES	NO	NA	
1.	Check for hacking of surface				
2.	Check door and window opening size for proper finish size				
3.	Check if corner of wall, wall and frame junction are plastered				
4.	Check for right angle at corners				
5.	Check for plastering mix ratio for uniformity and workability				
6.	Check for plastering in IB wall edges				
Project Name:		Building:		Floor:	
Checked By:		Room:		Date:	
Approved By:		Client:			

6. CHECKLIST FOR FIXING DOOR, WINDOW FIXING					
SL. NO	PARTICULARS	STATUS			REMARKS
		YES	NO	NA	
1.	Check door frame for plumb				
2.	Check size of door with drawing				
3.	Check shutter height in respect to finished tile level				
4.	Check for frame and shutter size and material				
5.	Check for no. of joints and connections as per drawing				
6.	Check if all the screws are locked in place for shutter				
7.	Check painting/finishing is done for door frame				
8.	Before installation, ensure proper plastering is done in openings of required thickness.				
9.	Check for damage, crack, termite attack				
10.	Check for uniform gap between frame and shutter				
11.	Check for direction of shutter swing				
12.	Check of ease of opening and closing				
13.	If protection cover is provided, ensure it is removed only after completion of project.				
14.	Check for door and window hardware of its specification and manufacturer				
15.	Ensure weather tightness of external door and windows				
16.	Check for ease of de-constructions connection usage				
17.	Check for accessible connections				
Project Name:		Building:		Floor:	
Checked By:		Room:		Date:	
Approved By:		Client:			

CHAPTER 6

SUMMARY AND CONCLUSION

6.1 CONCLUSION

Earthquake Resistant Building:

- The study shows that the Interlocking Blocks are suitable building material for earthquake resistant and quick rehabilitation buildings.
- They can be reinforced and combined with framed structural system to construct disaster resistant buildings.
- They are currently recognised and supported by government of Gujarat as disaster resistant building system.

Material Efficiency:

- The number of interlocking block required per cum is 274 nos for hollow soil interlocking block and 129 nos for solid cement interlocking block whereas number of block required for brick is 494 nos.
- The use of plaster is eliminated nearly upto 80% as the masonry work is exposed and plastering is used in column, beam, openings and junctions.
- The material can be reused and recovered to its 90-100% potential with minimum wastage as they can be de-constructed easily.
- Dependency on sand, cement, aggregate, painting, putty are all reduced.
- Equipment and tools required are simple and easy to handle.
- Any corrections in the work can be carried out easily without damage to blocks.

Labour Efficiency:

- The labour cost is 4.9% to 5.3% of the total cost of the block work which is very less compared to 30% in brick masonry system.
- The dependency on skilled labour is reduced as semi skilled and unskilled labour are only required.
- The construction is simple, easy, light weight, quick and all-season.

- The labour efficiency is 102 blocks per hour whereas its 60-70 blocks per hour for brick work.

Time Efficiency

- The time taken for construction is reduced as the full wall can be constructed in a single day instead of 1.5m restriction in conventional wall system.
- Various time consuming activities are eliminated such as wall finishing with putty, plastering and no curing time is required.
- The cycle time of each block arrangement (21 sec to 24 sec) is also less than that of brick as placing of mortar is eliminated.
- Total period of construction is reduced by 50% (45 days for IB while conventional construction takes 3 months).

Water Efficiency:

- The project can save upto 70% of its water usage because of the following reasons:
 - IB do not require to be wet before laying
 - IB do not require concrete mortar
 - IB do not need curing
 - Plastering is eliminated
- Interlocking block construction is suitable for areas which face water scarcity

Cost Efficiency:

- In case study - 1, the cost of masonry block work is ₹ 7,15,274.24 for brick block work and ₹ 18,92,385.91 for interlocking block work. It can be understood that the cost of block work using interlocking block is high in case study - 1 because of its construction methods and techniques such as reinforcement of IB walls due to its G+4 storey height.
- In case study - 1, the cost for plastering and painting/finishing is reduced from ₹3,32,484.62 and ₹ 4,52,594.39 to ₹ 1,57,056.20 and ₹ 84,556.81 respectively. The cost for painting and plastering is reduced in interlocking block system compared to brick masonry system.
- The material and labour cost of brick, compressed hollow soil interlocking block and solid cement interlocking block is given below:

Masonry System	Brick Block	CSIB	SCIB
Material Cost per m3	₹ 5222.21	₹ 7825.84	₹ 4672.84
Labour Cost per m3	₹ 2022.50	₹ 435.00	₹ 240.00
Total Cost per m3	₹ 7244.71	₹ 8260.84	₹ 4912.84

- In case study - 2, the cost of masonry block work is ₹ 1,85,367.11 for brick block work and ₹ 1,19,431.86 for interlocking block work. The cost of block is reduced by using interlocking block for the single storey structure as the construction techniques are simple and no reinforcement of wall is required.
- In case study - 2, the cost for plastering and painting/finishing is reduced from ₹ 1,65,806.06 and ₹ 1,15,946.39 to ₹ 11,807.04 and ₹96,140.59 respectively.
- From both the case study of single storey and four storey building using hollow interlocking block and solid interlocking block, it can be concluded that, interlocking block is financially viable for using in up to G+2 storey building only. Higher storey structures may cost higher to construct using IB.
- The cost saving can be achieved in plastering and painting works, labour cost savings.
- The single storey project can be constructed in 45 days time which helps in cost savings also.

Design for Deconstruction using Interlocking Block

- Interlocking Block is a suitable material for implementing design for deconstruction principles.
- The interlocking block masonry system can be used in flexible and temporary structures.
- We were able to achieve 85% deconstruction rating for interlocking block walls as they can be removed easily with minimum damage due to dry stacking and interlocking arrangement.
- As no plastering is done, the materials used in construction can be deconstructed using simple labour force and tools. The connections are simple and method of deconstruction is unchallenging.
- The hollow interlocking block is more difficult to deconstruct, mainly in buildings above low rise as they are reinforced, compared to solid interlocking block. The damages is also less in solid interlocking block and can be reused easily.

- f) But using hollow interlocking block shall help in separating MEP service from masonry system. In solid interlocking block, the MEP services are laid into walls by chasing of pipes and plastering.
- g) The Interlocking block shall be successfully used for DfD concept by following the framed guideline and construction technique along with framed checklist to ensure quality construction and deconstruction.

6.2 RECOMMENDATIONS

- a) The usage of interlocking block in high rise building is not yet experimented. The structural and load bearing characters and the stiffness offered by the IB masonry system as infill in a framed tall structure shall be studied and analysed.
- b) The Composition of the raw material used in IB can also be experimented and materials such as flyash, etc can be used to replace the cement.
- c) Other dry masonry techniques such as post tensioning, shall be studied to create alternative bonding instead of cement paste or slurry.
- d) The quantity of production shall be increased to make the IB readily available so it can replace conventional brick masonry easily.
- e) The blocks shall be made more affordable by mass production and substituting raw materials.
- f) The hollow interlocking blocks can also be used to create insulation walls with choosen filling materials.
- g) The various types of IB units shall be created along with half, U and full block to create blocks to be used for laying electrical and plumbing systems. Instead of chasing, conduit shall be placed isolated in blocks created specially for this purpose.

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