International Organisation for Migration

Flood Resilient Shelter in Pakistan

Phase 2: Evidence-Based Research

October 2017

IOM • OIM

UKaid from the British people

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Foreword

Executive Summary

Extreme flooding since 2010 has affected 35 million people and damaged or destroyed 2.5 million homes. By mid-2014, approximately 200,000 shelters had been implemented by various shelter organisations. This evidence based research study was subsequently commissioned by DFID and IOM with four objectives. The research has culminated in the production of two key deliverables responding to four objectives, this report captures objectives 1-3 and the accompanying shelter guide captures 4.

1. To substantiate the key criteria metrics developed for the 14 indicators during Phase I of this study through scientific testing and analysis.
2. To utilise the key criteria metrics to rigorously evaluate the performance of shelter constructed in southern Pakistan 2010 - 2102
3. To capture the methodology and key findings of the research in a research report, contributing to an academic and scientific evidence base on flood resilient shelter.
4. To make recommendations in a shelter guide that will inform best practice in the design, and implementation of flood resilient shelter in southern Pakistan.

This research primarily addresses flood resilience of improved vernacular construction for small-medium scale flooding, such as occurred in 2011, 2012. Flooding is the key hazard in the study area of Sindh Province and whilst there is also a risk from low to medium seismic hazard consideration falls outside the scope of this research. Some basic rules of thumb for improved seismic performance are included in the shelter guide nonetheless.

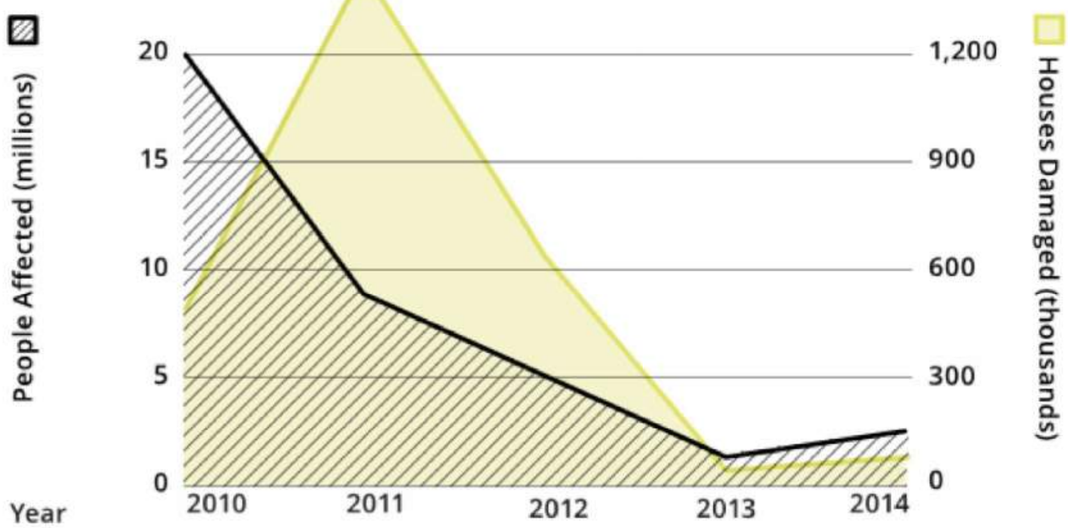


Figure 1 Impact of flooding in Pakistan

Five wall typologies were constructed in southern Pakistan following the floods: loh-kat, layered mud, adobe, fired brick and concrete block. Concrete was rarely used either before or after the flooding, but is included here as a baseline for future research. Fired brick was used extensively after 2010 floods as it was believed to be more durable, but increasingly focus shifted to improved vernacular construction such as lime stabilised adobe, with Adobe and layered mud being the most common typologies before the floods.

Common advice for earth construction is simply to avoid flood plains, an option often unavailable to communities in the study. This approach manifests itself in a lack of research on either flood damage or flood resilient design for vernacular construction, with notable exceptions referred within (IOM 2015, UN-HABITAT 2012, Heritage Foundation 2013, Alan M. et al 2008).

Location and settlement planning, both key to reducing vulnerability, are outside the scope of this study, as is the probabilistic hazard assessment that is required to inform land use planning.

The research was conducted between Jan 2016 – Aug 2017 by Arup on behalf of and in collaboration with IOM and funded by DFID. Local partners PEDA International and NED University provided critical local capacity for data gathering and physical testing whilst a Technical Advisory Group and End User Group reviewed progress.

Methodology

A phased research approach was adopted which included data gathering, analytical desk studies and physical testing. At each phase the research was given structure and rigour by three key performance criteria: 'safe and resilient', 'acceptable to occupant', and 'sustainable'.

Data was gathered via shelter assessments, homeowner surveys, and stakeholder consultations. PEDA International were selected as a credible local partner to conduct the shelter assessments and homeowner surveys on the basis of logistical capacity, appropriate skills and experience, robust quality control measures and lack of involvement and hence bias in the shelter response. A statistically representative sample of 800 shelters was surveyed across 13 districts over 19 weeks. Teams of two collected both quantitative and qualitative data against the key criteria. Their survey teams were trained in use of rigorously designed electronic survey tools which helped to ensure consistency, completion, remote monitoring via an online dashboard and quality control. In addition, 10 semi structured interviews were conducted with key informants from shelter agencies. Limitations in data collection included: relying on recollection of events up to five years earlier; only 6% of surveyed shelters had experienced flooding; 3% of shelters had been abandoned; and approximately 15% of respondents declined to participate.

Analytical desk studies were conducted by Arup specialists to scientifically evaluate and compare existing shelter and substantiate the metrics for the key criteria, making reference to appropriate international best practice. These studies addressed structural design and performance; thermal comfort, ventilation and air quality; daylighting; cost; and sustainability. Structural analysis included a review of codes and guidance; the capacity of foundations, walls, and roofs; connection details; stability; and a review of the design information provided by the shelter agencies. Daylight, thermal comfort, ventilation and air quality were evaluated using the field data collected and independently simulated using basic computer modelling to test improvements. Capital and lifecycle costs were quantified and analysed based on bills of quantities provided by shelter agencies. Sustainability was studied to analyse the local supply chain, natural resource use, material availability, labour standards and embodied energy/carbon and waste. Transportation and material production factors were estimated from a range of industry sources.

Unique full scale flood and rain tests were conducted to evaluate the relative performance of different improved vernacular construction techniques, inspired by existing designs as well as best and worst case reference panels. NED University in Karachi were appointed to conduct the testing as they had experience of full scale vernacular construction testing, rain and flood modelling expertise, material testing equipment and are located close to the study area enabling materials and labour to be brought in. 24 full scale wall panels of varying material typologies were subject to simulated meteorological and anecdotal flood and rain conditions from the study area. Measurements included capture and quantification of eroded material, a detailed photographic record and a live video feed.

Key findings

The culmination of the data gathering, analysis and physical testing was that all five wall typologies were ranked (1-5, high-low) for performance against each indicator within the three key criteria of safe and resilient, acceptable to occupant, and sustainable. Ranking was developed in preference to a weighted score to avoid inherent complexity and subjectivity. A number of findings cut across the wall typologies and are summarised here first. Subsequently the wall typologies are grouped together and discussed in more detail in accordance with similarities in the materials and construction systems 1. Adobe and layered mud, 2. Loh-kat and 3. Fired brick concrete block.

There is a need for clarity in design approach to flood and rain hazard if investment in DRR is to be of value. Field survey data highlighted that measures that rely on being built up to or above the flood level, were commonly built below the level of the most recent flood. Physical testing has shown that DRR measures that are effective in resisting standing water are notably different to those that resist heavy rain.

Wall typology	Loh-kat	Layered mud	Adobe	Fired brick	(Concrete block)
					
Safe and Resilient	3.2	3.8	3.8	4.0	(4.5)
Beneficiary Acceptability	2.9	4.0	3.7	4.7	(4.4)
Sustainable	4.7	4.5	4.5	1.7	(2.5)
Total	**3.4**	**4.0**	**3.9**	**3.7**	**(4.1)**

Table 1 Average rankings for wall typologies against each of the key criteria

A) Heavy rain	A) Standing water
	Measures to keep shelter standing:
1. Water resilient plasters	1. Foundations to adequate depth in original ground (not fill material)
2. Roof overhang	2. Waterproof materials such as stabilised soil to above level of standing water
3. Drainage	
4. Toes or plinth protection and other sacrificial mass	
5. Stabilisation of mud roof	**Measures to keep belongings dry:**
	3. Platform (external dry area)
	4. Raised floor (internal dry area)
	5. Shelf (limited internal dry area)
	6. Accessible roof

It is recommended that design information and even physical shelters are clearly marked with a line to indicate the maximum standing water level which they might withstand.

Table 2 The purpose of DRR measures

The need to reduce cost (and carbon) but maintain water resistance led to increased use of lime in stabilising earth construction from 2010 – 2012, a notable good news story. Physical testing confirmed both the great benefit and drawback of lime: it has the potential to produce cheap and environmentally friendly waterproof earthen construction, but can easily be undermined by workmanship as it requires careful mixing, curing and testing to be effective. Training is essential and programmes implemented towards the end of the response should be rolled out across the flood affected areas.

This research has shown that there is a clear link between the quality and completeness of design information and the quality of what is built. Design drawings and the technical guidance on which they were based were generally found to be lacking, culminating in an absence of basic construction detailing such as ring-beams and lintels in the field, confirming the need for the shelter guide. As shelter organisations move towards supporting self-recovery the challenge of how to covey resilient shelter design will become even more acute and creative solutions will be required.

Diverging from conventional wisdom thermal performance was found to be largely divorced of material typology as a result of the dominant effect of ventilation provided to a small space by an open door, as the room quickly reaches a similar temperature to that in external shade. Computer modelling demonstrated that orientation, cross ventilation, roof and wall thickness can all serve to improve performance. Daylighting was a low priority for homeowners who in many cases blocked up openings, presumably to provide security and or privacy. Basic computer modelling has shown that brick/block Jali screens can provide a robust, secure and private opening whilst maintaining adequate daylighting. (Jali screen photo)

On the whole foundations were found to be adequate, there is however room for improvement in wall thickness and other structural rules of thumb such as size and location of openings. Survey data suggested that roof performance in terms of leakage is unrelated to slope or material, again contravening popular wisdom. Roof connections were often omitted with 73% of simply resting on the walls and 33% of respondents reporting that their roof had lifted off in high winds.

On the whole shelter agencies did a good job of adapting their designs to account for material shortages, local skills, profiteering and child labour, although concerns over quality were widespread and were exacerbated by ineffective timber/bamboo treatment and non-durable design detailing.

The sustainability and cost analytical desk studies have shown that cost of and embodied carbon in shelter construction materials are proxies, such that expensive shelter such as fired brick also contain the most embodied carbon.

Adobe and layered mud

Evaluation of existing shelter indicated that adobe and layered mud give the best all round performance whilst physical testing has shown that performance may be further improved through stabilisation and detailing for durability.

They are cost effective and contain low embodied carbon, albeit slightly more than loh-kat in both cases. The materials required to maintain them are easy to obtain and are more likely to be repaired by an unskilled worker. They require more frequent, but less expensive repair than fired brick shelters, primarily to repair rain damage. Physical testing has shown that durability could be significantly improved and maintenance reduced through the 'hat and boots' approach, incorporating a roof overhang, lime stabilised earth plaster and some form of base protection.

The water resilience of adobe and layered mud is dependent on successful stabilisation using either lime or Portland cement, with physical testing illustrating that they may achieve the same performance as fired brick. In either case training is essential in order to understand soil suitability, mixing and curing. Testing of the finished product, such as by placing an adobe block in a bucket of water to check that it does not dissolve, is essential. A key limitation of layered mud is that it is built in-situ and cannot easily be tested in this way.

Both adobe and layered mud in particular are low strength load bearing construction. The process of compacting earth into a mould to make an adobe block will typically make it stronger than layered mud and so from a structural and durability point of view is preferred. However, this process takes additional time and effort, with homeowners anecdotally reporting that they preferred layered mud as a result.

Loh-kat

Viewed variously as a poor man's material or else as a transitional typology, loh-kat shelter were constructed rapidly and cheaply for homeowners who had an average income one third of those who received fired brick shelters. The suspicion is that the defects and poor performance described herein is not inherent but at least partially engendered by the approach to the typology.

They were found to be the largest shelters by some way, space being a priority for many homeowners, possibly as they were the cheapest to construct. They also contain the least embodied carbon.

The Loh-kat wall typology was adapted to account for material shortages, with some walls built from bamboo frames and reed matting. Loh-kat walls were more likely to tilt and lean, perhaps due to the use of bamboo frames, a 'new' technology, and the resulting omission of required diagonal bracing. As demand spiked the quality of bamboo dropped and with effective protective treatment largely unavailable durability is a key concern. Loh-kat deteriorated at a greater rate compared to other typologies, requiring regular but cheap and unskilled maintenance, with shelter agencies anticipating they would last a handful of years at most. Physical testing has shown that the burden of maintenance would be significantly reduced by use of stabilised plaster. Wall-foundation connections in particular require careful detailing to prolong rot, adding complexity to construction.

If well connected together the frame of a loh-kat shelter has the potential to resist small to medium scale flood events as the plaster is simply washed away whilst the frame ensures that the roof remains in place.

They were reported as less secure and less private than the other typologies, citing transmission of sound and ability to break through walls. They also have the highest risk of fire due to use of combustible materials, especially where the internal face is not plastered.

Fired brick and concrete block

Fired brick is the most expensive and contains the most embodied carbon of all of the materials. Concrete block contains less carbon than fired brick but more than the other typologies and is expensive also. Whilst they are stronger, more durable and have inherent water resistance they require more expensive maintenance by a skilled labourer, with materials that are less available, concrete block in particular is rare.

A minority of fired brick shelters had their performance undermined by use of mud mortar and or unstabilised earth foundations, both of which could lead to failure in even a small flood event, undermining the significant investment made in the bricks in the first place.

Homeowner surveys found that they are perceived as being more secure and private than other typologies and if given a choice 91% would prefer to live in a fired brick shelter.

Finally, the use of child labour in brick kilns is a serious concern that led some agencies to switch material typologies.

1
Introduction

For three years in a row, 2010-2012, extreme flooding occurred in southern Pakistan causing widespread devastation, resulting in more than 2.5 million houses being destroyed. Humanitarian donors and agencies implemented shelter programmes in response to these events which assisted in the re-construction of 200,000 houses. However, their capacity is dwarfed by the magnitude and frequency of these flood events, with an estimated 90% of those affected left to self-recover. Given the likelihood of increased food risk and limited humanitarian funding in the future, it is therefore imperative to enable communities living in food-prone areas to build food-resilient shelters.

Phase I of this study, conducted in 2014, drew together existing information on flood-resilient shelters in order to identify key criteria that shelter partners and government can use to inform and assess the design of flood-resilient shelter in southern Pakistan. The literature review highlighted that there is limited academic literature on flood-resilient shelter and a documentation review found that existing shelter assessments do not consider flood resilience and tend to focus on collation of lessons learned rather than scientific evidence. Phase I generated three outputs: an Excel database of the shelter response 2010-2012; valid and reliable metrics for assessing shelter designs; and a research methodology for Phase II. Whilst the study is based upon an evaluation of shelter agency programmes most of the findings will remain relevant as the shelter community switches focus to explore how to support self-recovery.

1.1 The study

The overall aim of Phase II research was to conduct a scientific study on post–flood shelter projects implemented by agencies in southern Pakistan in order to develop a shelter design guide that will contribute to building the resilience of communities living in flood-prone areas in southern provinces of Pakistan.

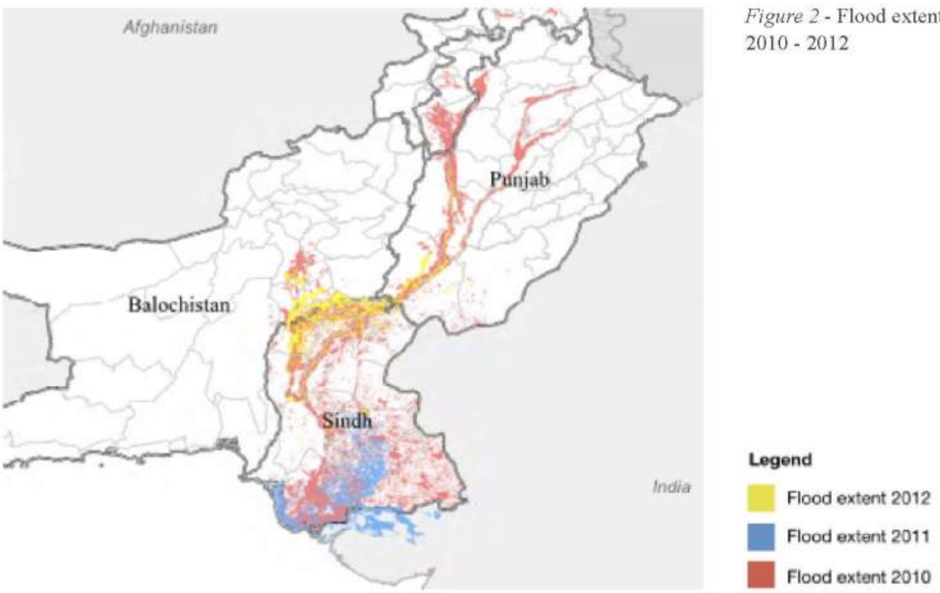


Figure 2 - Flood extents map 2010 - 2012

The specific objectives are:

1. To substantiate the metrics developed for the 14 indicators during Phase I of this study through scientific testing and analysis.
2. To utilise the metrics to rigorously evaluate the performance of shelter constructed in southern Pakistan 2010 - 2102
3. To capture the methodology and key findings of the research in a research report, contributing to an academic and scientific body of evidence on flood resilient shelter.
4. To make recommendations in a shelter guide that will inform best practice in the design, and implementation of flood resilient shelter in southern Pakistan.

1.2 The report

This research report is one of two key project outputs. It presents the methodology and key findings of the study and is accompanied by a shelter guide which details recommendations for flood resilient shelter.

The context, including prevalent shelter construction typologies and the characteristics of flooding in the area are described in section 1. The approach and methodology of the study are described in section 3, which highlights reasoning behind decisions made, the challenges faced, and the limitations of the results. The intention is that the methodology can be interrogated and built upon by others such as academics and shelter agencies who are conducting research in this area.

In particular, the final key criteria and associated metrics (See Appendix B) provide a scientific framework around which further research could be designed and conducted.

The key findings are summarised against the three key criteria in sections 5 to 8 providing an evidence base for the wider shelter community including shelter agency staff. Critically this evidence base supports the recommendations made in the shelter guide which are provided in the form of best practice shelter designs and a decision making tool. The link between the key findings in the report and design principles section of the guide are facilitated by common headings and whilst written as standalone documents they are inherently complimentary.

The report concludes in section 9 with observations and recommendations for further work on this topic.

2
Context

2.1 The Typologies

The materials used to construct shelter are key to their flood resilience. The evaluation and comparison of performance within this study refers to five material typologies which were identified in Phase I as having been constructed in southern Pakistan since 2010: mud, adobe, loh-kat, fired brick and concrete block. This section clarifies and outlines differences between and within the typologies, including categorisation of the structural systems and methods of construction, how the materials were sometimes employed in combination and the frequency with which they occurred.

Of the five wall typologies four are loadbearing whilst the fifth, loh-kat relies upon a framework of vertical and lateral timbers which are plastered either side. Loh-kat is typically lighter weight with foundations made by simply embedding the vertical timbers into the ground. Of the four loadbearing typologies three can be considered as masonry as they are assembled from pre-made units whilst layered mud is built by hand in-situ. The loadbearing typologies require strip foundations in order to support them, with trenches dug and subsequently filed with masonry or compacted soil. Roofs may be flat, singled or double pitched and in some cases conical where a shelter is round on plan, although no round shelter were found in the random field survey.

Figure 3 - Five wall typologies: from top left clockwise loh-kat, concrete block, Adobe, layered mud, fired brick

Within each typology properties such as strength, water resistance and durability may vary significantly according to the constituent components and the process through which they were made. A well-made soil block that has been stabilised by adding lime, may outperform a poorly made fired brick that has been assembled with unstabilised mud mortar.

Before the floods 80% of houses in Sindh were either adobe or layered mud. Concrete block construction was not present prior to the floods (UN-HABITAT 2010) and only used for 1% of shelters built during the response. This is supported by the Phase I database and reinforced by the data gathering (See table X – data gathering limitations). Despite this scarcity, it was decided to retain concrete block in the study for completeness as it is widely used elsewhere, and its use could increase in the future.

Following the 2010 floods, humanitarian agencies typically re-constructed houses in fired brick as it was considered more durable. Subsequently, awareness that flooding was becoming an annual event, together with limitations in funding, have led to increasing emphasis on low-cost vernacular solutions that incorporate flood-resistant features.

As focus switched to improving vernacular typologies a number of hybrid designs were implemented whereby more expensive water resistant materials (such as fired brick) were utilised for foundations and lower wall, with cheaper, less water resistant materials such as adobe or loh-kat above.

Traditional Loh-kat construction consists of a lattice of interwoven timber strips or branches plastered either side with similar variations in existence all over the world. By contrast some Loh-kat shelters built in the response consisted of a bamboo frame with verticals at increased spacing and a read matting known as 'chicks' fixed to one side. Key informant interviews suggest that this was a response to material depletion, a factor which could help to explain the relatively poor performance of this wall typology under certain criteria.

Figure 4 Loh-kat panel at testing facility made from bamboo frame and chicks matting. The next step is to apply plaster to the chicks matting. Note that the bamboo frame requires lots of diagonal bracing in order to make it stable. With many loh-kat shelters recorded as visibly leaning over it is most likely due to insufficient bracing.

2.2 Flooding hazard

The floods in 2010 were an extreme event, caused by cloud bursts mixed with seasonal snow melt in the mountainous northern areas of Pakistan. Deforestation of natural forests in upland catchment areas for timber and fuel served to increase the severity of flooding. This led to riverine flooding that affected the entire Indus River valley, with standing water in places over 8ft destroying or damaging over 1.7million homes (DEC 2012).

The flooding in 2011 and 2012 was less severe, but representative of the type of food events that occur almost annually. In 2011, record rainfall over the flat lands of southern Sindh overwhelmed drainage canals and led to ponding with standing water of 3-4ft. The following year heavy cloud bursts over the equally flat northern Sindh and southern Punjab also resulted in standing water of 3-4ft which remained for several weeks until it evaporated or was pumped out. Flood duration in the Sindh is known to be extended by lack of a natural 'return flow' mechanism whereby flood water is unable to drain into the (Indus Tariq, M & Giesen, N. 2012).

Meetings were held with UNESCO, the Flood Forecast Division (FFD), NED University and the Irrigation Department in an attempt to source hazard data. The later reported that they have data on flow characteristics at barrages along the Indus, but not for the inland study area. Flood extents maps (http://www.sgs-suparco.gov.pk/floodhazard/default.aspx) from previous events are available via a collaboration between UNESCO and SUPARCO and whilst historical events provide a clue to what may happen in the future there is a need for a probabilistic hazard mapping to determine both the future likelihood and the severity of flooding (See section 9 – Recommendations for further work).

Year	Duration (weeks)	Depth (feet)
2010	11	5.1
2011	9	3.4
2012	10	3.7
Total	10	4.0

Table 3 Depth and duration of flooding reported in homeowner surveys

2.3 Damage to shelter

A review of literature focusing on the impact and measurement of flood damage on shelter highlighted that there are limited scientific studies available. A Rapid Technical Damage Assessment (UN-HABITAT 2010) conducted by UN Habitat following the 2010 floods does categorise damage and whilst it would benefit from greater definition between categories it provides a useful reference point. The study suggests that the primary cause of failure was undermining of foundations whilst damage due to submersion in water accounts for just 15% of failures, which is surprisingly low.

Existing guidance for earth construction (Houben, H and Guillaud, H. 1994) simply recommends to avoid flood plains, an option often unavailable to communities in flood prone areas of Pakistan. This approach manifests itself in a general lack of research into flood resilience of vernacular construction, with a study conducted by Heriot-Watt University into flood response of cob (earth) walling stating that "This paper is believed to be the first preliminary investigation into the effect of flooding on cob structures" (Alan M. et al 2008). Key findings stated that compaction and inclusion of straw both improved performance of cob subject to standing water. Previous practical investigation of capacity to withstand sustained immersion/ rainfall in Pakistan is limited to a notable study conducted by Strawbuild (IOM 2015) with lime stabilised earth blocks remaining intact in buckets of water for over a year. Further detail on the impact of flooding on shelter can be found in the Appendix E.

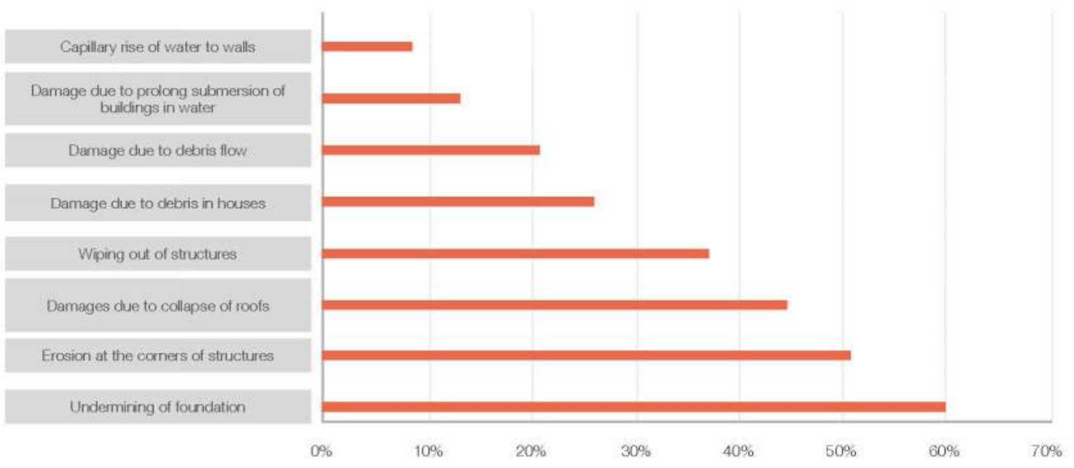


Figure 5 – Major causes of collapse due to mud houses in flood affected areas (UN-HABITAT 2012)

3
Scope and approach

3.1 Scope

This study was led by Arup International Development (Arup) on behalf of the International Organization for Migration (IOM), who lead the Shelter Cluster in Pakistan, and supported by the Department for International Development (DFID). It was completed over a period of 20 months between January 2016 and August 2017.

Arup and IOM teams collaborated closely for the duration of the project and on the data gathering and physical testing activities in particular, where IOM's experience, contacts and in country presence were invaluable. Local partners were engaged by Arup to broaden the skills and capacity of the project team and to act as local centres of knowledge. PEDA International were appointed to conduct data gathering in the field and NED University were appointed to conduct and reporting on physical testing and assist in their design. See Appendix A for an illustration of the project team.

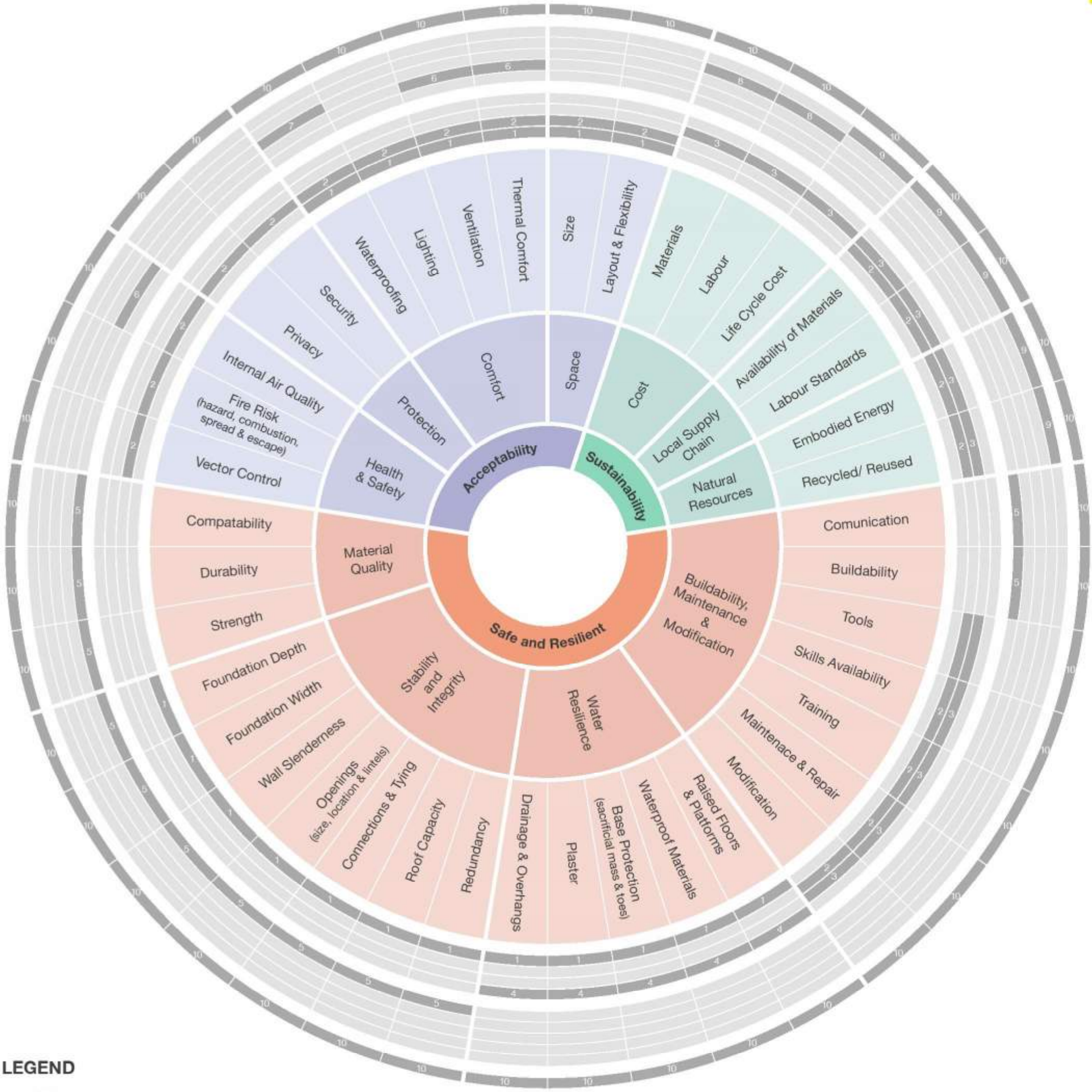
A Technical Advisory Group (TAG), consisting of international shelter agency experts and an End User Group (EUG) of programmatic and technical shelter agency staff in Pakistan were convened to review key milestones including the data gathering survey forms, ideas for physical testing and the two final outputs.

The study relates to the area of southern Pakistan comprising Sindh province and southern Punjab. It is anticipated that it will have relevance across the region.

The focus of this study is how the design of shelter using vernacular forms of construction can improve the food-resilience of communities to medium scale flood events, such as occurred in 2011 and 2012. This includes preventing damage caused by heavy rain which can wash away walls and weaken structures. The recommendations respond to hazard levels, such as depth of flooding, but are unable to give the likelihood of occurrence in a given location. This would require a probabilistic hazard study and is outside of the scope of this study. Location, settlement planning and infrastructure also play a critical role in reducing vulnerability to most flood events and extreme events such as occurred in 2010 in particular, but are outside the scope of this study. This requires regional food risk management strategies and land-use planning that is informed by hydrological modelling, and an understanding of changing weather patterns.

On the Global Climate Risk Index for 2017, Pakistan ranks 7th on the list of 10 countries most affected from natural disasters from 1996 to 2015. With global trends such as climate change contributing to a likely increase in the frequency and yearly impact of natural disasters and limited humanitarian funding in the future there has been a shift of focus to explore how to improve resilience of entire communities through self-recovery. In this context it is important to recognise that the findings and recommendations of this study are based upon data drawn from assessing and evaluating shelter that was supported directly by shelter agencies. Whilst they are anticipated to remain relevant to self-recovery, to confirm this would require further work.

Southern Pakistan is also at risk from low-medium seismic hazards, as evidenced by the earthquake in Baluchistan in September 2013, whilst tsunami and cyclone hazards are relevant in coastal zones. Consideration of these hazards falls outside the scope of this study, but is nonetheless critical to the design of safe and resilient shelter in this region of Pakistan.



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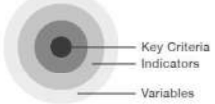


Data Gathering
1. Shelter Assessments
2. Homeowner Surveys
3. Key Informant Interviews
4. Physical Testing

Analysis Desk Study

5. Structural
6. Thermal, Comfort & Ventilation
7. Daylighting
8. Cost
9. Sustainability

10. Comparative Analysis

Refer to the Appendix for a table of the associated qualitative and quantitative metrics

Figure 6 – Key criteria, indicators and variables and research activities

3.2 Approach

This study followed a phased research approach, including data gathering through 800 field surveys, consultations with shelter agencies, full scale physical flood and rain testing of key shelter components and specialist desk studies to analyse and interpret data gathered against appropriate international best practice. All activities were framed by the key criteria (see figure 6), providing the necessary structure and rigor to the study, whilst the research process served to iteratively refine and substantiate the criteria and associated metrics.

Phase II began by refreshing a database of agency supported shelter that was compiled during Phase I and from which a statistically representative survey sample was selected. A local partner was appointed to conduct technical shelter assessments and gather opinions through homeowner surveys. The local partner separately held structured interviews with shelter agencies to gather data to compliment the field surveys. An Arup field mission to Pakistan was held at the start of the data gathering phase to provide training and trial the tools that were developed, to gather data on flood hazard and make initial enquires into testing facilities.

An initial analysis of the data gathered identified objectives and informed the design of the physical testing phase, with a second local partner engaged to assist Arup and IOM to design, construct and conduct full scale rain and flood testing.

Analytical desk studies were conducted by specialists to review data gathered in detail, carrying out hand calculations and building basic computer models, with results benchmarked against appropriate standards and supplemented with further research where required.

Each of the previous phases was subsequently drawn together in a comparative holistic evaluation of existing shelter with a simple ranking system devised to score the five wall typologies against the variables in the key criteria. In parallel scoping of the two final outputs was initiated through consultation with local stakeholders during a second Arup field mission.

Section 4 details the methodology of each phase of the project, highlighting key considerations, limitations and challenges faced such that future studies might build upon the work done.

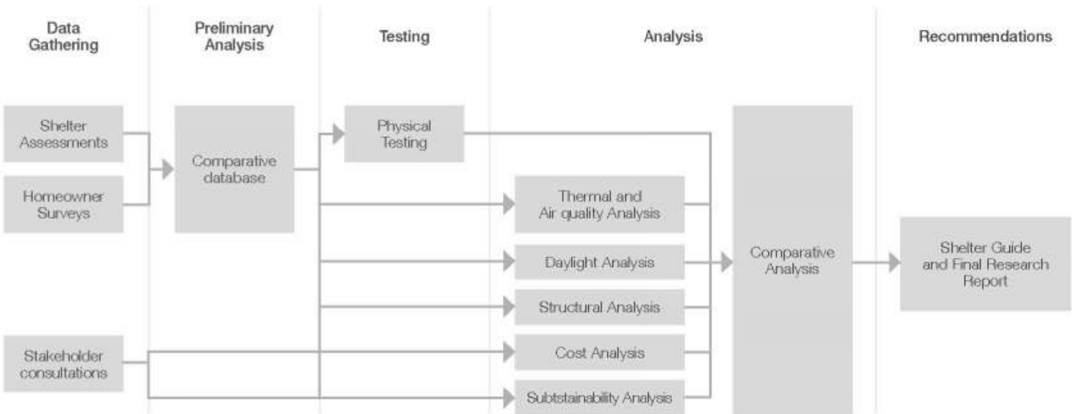


Figure 7 - Research process flow chart

4 Methodology

4.1 Data gathering

The purpose of the data gathering phase was to collect information on existing shelter against each of the three key criteria in order to facilitate further desk analysis (see section 4.2) and to help inform design of physical testing (see section 4.3) and subsequently to conduct a holistic comparative evaluation of shelter performance. Three data gathering methods were identified during Phase I and were refined during Phase II:

1. **Shelter assessments**
   Statistically representative field survey of 800 shelter. Quantitative data such as measurement of dimensions and qualitative data such as observations of technical aspects of the shelter collected by a technical person who understands shelter terminology such as an engineer.
2. **Homeowner surveys**
   Statistically representative field survey of 800 shelter. Qualitative data capturing the opinions of the homeowner collected by a community surveyor.
3. **Stakeholder consultations**
   Key informant interviews with up to 10 shelter implementation agencies selected for their involvement in the response and ongoing presence in Pakistan.

With the credibility of the study resting on the data gathered a number of requirements were identified:

- A **credible local partner** to conduct data gathering,
- **Rigorously designed data gathering tools,**
- **A statistically representative sample** and,
- **Robust quality assurance**

- 800 surveys, with up to 379 data points
- Target of 40mins per survey; 6 shelters per day; maximum of 6 shelter in any one village
- The surveying took 19 weeks, approximately 4 months
- 6 people (4 men and 2 women) broken into 3 teams of 2 people to conduct shelter assessment and homeowner survey of the same shelter simultaneously
- Sindh (and Punjab) provinces, 13 districts
- 29 implementing partners, 9 donors

Table 1 Shelter assessment/Homeowner survey – key stats:

Credible local partner

Following circulation of a call for interested parties and joint Arup/IOM evaluation of proposals PEDA International were appointed to conduct data gathering on the basis of the following criteria:

- Logistical capacity and a presence in the study area to deliver surveys of up to 1000 shelters in remote villages in 12 weeks
- A balanced team of technical and non-technical data gatherers with strong project management skills to oversee. Mixed gender teams were required for consultations, ensuring that gender was not a barrier for the homeowner surveys.
- A realistic project delivery plan including adequate resourcing, travel plans and robust quality control measures.
- Not involved in shelter implementation during 2010 -2012 and free from any associated bias.

Rigorously designed data gathering tools

The key criteria provided the framework that drove the design of the shelter assessments, homeowner surveys and key informant interviews, with figure 6 providing a visual representation of how the activities relate to the key criteria. Reference was made to previous surveys, notably those conducted by Heritage Foundation (2013) of construction issues in the field.

Detailed design of the tools was developed based on the requirements of the analytical studies which were to follow on from the data gathering and would be reliant on collecting the right information. Methodologies were written early on for the five studies, helping to define the inputs which would be required. Undertaken by different specialists it ensured that the holistic aims of the study were rigorously met, it also served to generate a wealth of content and competing demands for data collection which became overly detailed in some places (see table 8 – lessons learnt).

Equipment	Purpose
Moisture meter	For measuring the moisture content of the walls at the bottom, middle and top
Therma-Hygrometer	For measuring humidity and air temperature both inside and outside the shelter
Infrared thermometer	For measuring the surface temperature of the walls, floor and ceiling
Laser measure	For measuring distances quickly with a single person
HDR camera app	Used in conjunction with a colour chart placed on the surface which is being photographed this app is for measuring 'true' colours to help determine reflectance values

Table 4 - Equipment for data gathering

The shelter assessments and homeowner surveys were developed internally by a team of specialists and reviewed externally by the Technical Advisory Group. Shelter assessments were subsequently re-ordered to reflect the sequence that a surveyor would gather data, for example by grouping all data on the roof together.

Statistically representative sample

During Phase I a database of one room shelters constructed through shelter agency programmes following floods (2010-2012) in Sindh province was compiled. This was updated with new information from the shelter cluster lead, particularly for 2012, bringing the total number of shelters in the database to approximately 200,000.

For the findings of the research to be credible a comprehensive data set and statistically representative sample size was required. In order to compare relative performance between the five material typologies the sample was stratified and an online calculator (http://www.raosoft.com/samplesize.html) was used to determine a statistically representative sample within each typology. Sample size was determined assuming a confidence level of 95% and margin of error of 7%.

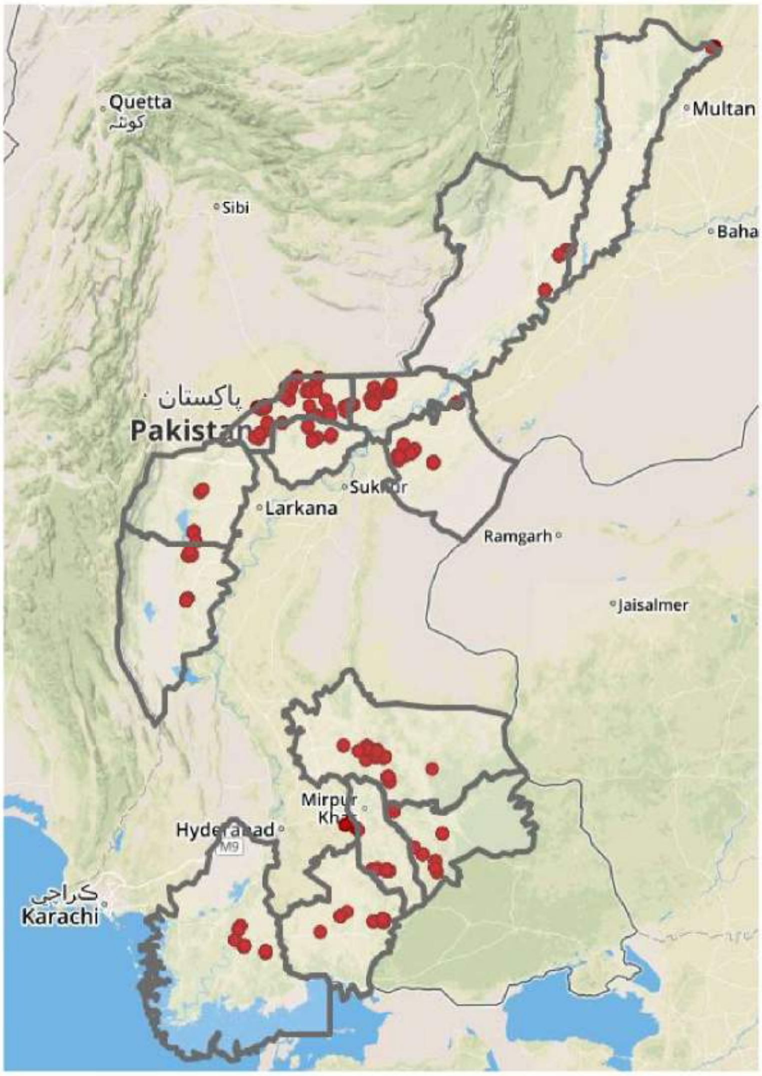


Figure 8 - Data gathering study districts and villages

	One room shelters	Calculated sample size	Actual sample size
Adobe	67,503	196	192
Fired brick	46,492	196	192
Concrete blocks	4,072	188	33
Loh-kat	35,511	196	197
Mud	18,784	196	186
Unknown	32,710	0	0
TOTAL	205,072	972	800

Table 5 - Statistically representative sample stratified by wall material typology

For logistical reasons it was decided to focus on the 11 most flood affected districts in Sindh Province, which in turn was the most flood affected province. This represented 90% of all one room shelters in the database built in Sindh. Two additional districts in Punjab were included in the study at the request of the National Disaster Management Authority. The sample size for a given material typology was then assigned proportionally to the districts where they were built.

Villages that met the material and location sample criteria were selected at random using an online random number generator (https://www.random.org/integers/). In order to control costs associated with logistics and travel between remote villages a maximum of 6 shelters were surveyed from any one village.

In 33 villages the local partner found that the shelter material typology on the ground differed to the records provided by implementing agencies in the Phase I shelter database, with concrete block the most frequent offender. The local partner felt that this discrepancy would trace back to implementing agencies, rather than village level, where agency oversight would prevent donated materials being sold or swapped.

Robust quality assurance

Quality of the data collected was ensured through training, trial and adaption of survey tools, and subsequent monitoring of the fieldwork.

A two-week field trip was held for the survey designers to provide training on project background, purpose and equipment to the local partner and incorporate their feedback. Field trials were an essential step in familiarising the local partner with the format and content of the forms with each survey adjusted based on feedback in order to improve usability and ensure that multiple choice options reflected condition on the ground. A steep learning curve saw the initial time to complete one survey reduced from two hours to between 30 and 40minutes.

An online dashboard (map and database) enabled real time monitoring of progress once surveys were underway, with pin drops and associated survey data loaded to the cloud as surveys progressed. 10% of all surveys were selected at random for detailed review with comments passed back to the local partner via a weekly progress call.

Wall material typology	No. of villages
Concrete block	19
Fired brick	2
Adobe	6
Loh-kat	5
Layered mud	1
Total	33

Table 6 - Villages where wall typology on the ground varied to that given by agency in database

Digital data collection advantages:	
Monitoring of quality and progress:	Time and GPS location are logged automatically within the survey form. Once uploaded to the online platform, completed surveys can be viewed on a map and a linked database, allowing real time monitoring.
Completeness of data	Nearly all questions were mandatory to complete, such that a form could not be uploaded unless answers were selected.
Ease of processing and analysis	All questions are restricted to multiple choice ensuring uniform data response. In some cases an 'Unknown' or 'Other' field would be included. Multiple choice options were updated based on field trials. Automatic generation of database, eliminating need for manual data entry which is time consuming and prone to error, Photos are embedded in surveys.
Ease of use	Inbuilt visibility rules allows the form to adapt to previous answers that have gone before, with questions hidden as required. This aspect of the design required careful testing to ensure that the rules that governed visibility were correct.
Note: Field surveys were designed, collected and monitored using Fulcrum (http://www.fulcrumapp.com/) a web based software that can be used on smart phones and tablets.	

Table 7 - Digital data collection advantages

Time: Shelters constructed up to 5 years prior to the surveys impacted the reliability of data collected from homeowners.

Concrete block: Insufficient concrete block shelters were found in the field for a statistically representative sample to be collected. The results are included in this preliminary report but must be treated with caution.

Flooding: Only 6% of shelters visited had flooded since construction which is an insufficient sample from which to draw conclusions.

Hidden details: A number of questions in the surveys concerned building details that are hidden such as: use of lime or cement in mixes for foundations/walls/mortar/ plaster, foundation depth, lintels and ring beams (behind plaster). In these cases the responses are reliant on the memory of the homeowner. 91% of those surveyed were involved in the construction of their shelter so would have had first-hand experience.

Equipment: The decision to purchase therma-hygrometers and infra-red thermometers ensured quantitative data was gathered, whilst laser measurers helped speed the process of conducting the surveys. Conversely moisture meters and the HDR camera app both failed to gather useful data, with both being sensitive to how they are used.

Location data: Location data supplied by agencies was grouped by village in the database, so a single entry in the database could represent 70 shelters. Without a unique identifier it was not possible to select individual shelters randomly, raising the potential for selection bias to be introduced, for example by village representatives guiding the field staff towards shelter that had performed particularly well or badly. In order to try and mitigate against this the local partner would ask the community focal point 3 questions:

1. How many shelters are there in the village?
2. How many were donated?
3. How many of the donated shelters a) are badly damaged or b) abandoned gaps in the database served to exacerbate issues with location of shelter.

Abandoned shelter: Community focal points reported that 52 shelters were abandoned in the villages visited, representing 3% of the total shelters donated to those villages. A further 133 were reported as badly damaged, representing a further 7%. Surveys rely on homeowners being present to ask questions and the sample does not include abandoned shelters which potentially excludes the poorest performing shelters from the data set. The surveys did not record the material or reasons why shelter had been abandoned.

Hostility to the study: Citing broken promises from agencies of shelter and cash grants, approximately 15% of the villages visited refused to take part in the study. Lack of uniformity from one shelter to another was another common grievance among beneficiaries, highlighting the need for common design guidance for implementing agencies.

Complexity and length of surveys: Overall the surveys would have benefitted from being shorter and in places the questions were too ambitious in the detail they attempted to collate. Ultimately similar or better results could have been achieved through shorter, simplified questions. For example:

- A series of questions attempted to differentiate between thermal comfort during winter and summer at day and night. A generic question on thermal comfort would have sufficed.
- Questions on recycling and reuse of materials proved too complex and also could

Table 8 - Data gathering limitations

Locating villages: Locating randomly sampled villages was complicated by missing or erroneous data in the database. As shelter cluster lead IOM facilitated contact with implementing agencies on the ground, who in some cases were able to assist with locating the sample. In some cases the Implementing Agencies had since left the study area or were otherwise un-contactable in which case a new village was randomly selected.

Infrastructure: Travelling long distances to remote villages was slowed down by lack of roads and mobile networks.

Weather: Delays to the programme meant surveying extended into summer

Technology: Low lighting and absence of flash on the tablets meant that quality of photos inside the shelters suffered. Remote locations reduced frequency at which data could be uploaded to the cloud causing tablets to slow down.

Table 9 - Data gathering logistical challenges in the field

Figure 9 - Abandoned shelter

Key informant interviews

10 semi-structured interviews were held with key shelter agencies (See table 10) to collate data against the key criteria that the field surveys could not address; primarily within the sustainability and acceptability key criteria. A template was developed (refer to Appendix D) which was trialled and adapted with the local partner. Meeting records produced by the local partner were reviewed.

A guide to conducting the interviews was prepared by the Arup team in order to aid the local partner and ensure that the data gathered was useful. Key topics were identified and an approach was designed. More specific closed questions were also included as examples, See Appendix A.

Agencies were required to send one technical and one programmatic staff member to each interview. The data gathered was subject to the veracity of the interviewee's memory as four to six years had elapsed since the response. Indeed the local partner noted that care was required to restrict the conversation to the 2010 – 2012 flooding response, avoiding digression onto more recent earthquake reconstruction programmes.

Whilst the semi structured interviews were suited to gathering opinions and experience it was often necessary to follow up by email with specific questions to clarify numerical data gathered. For example initial data on construction programmes gathered during the interviews was clarified by emailing templates to the interviewees to ensure consistency of data.

4.2 Analytical desk studies

This section summarises the methodology followed for five analytical desk studies. The purpose of the desk studies was to scientifically analyse the data gathered from field surveys and key informant interviews supplementing it with international best practice in order to evaluate and compare existing shelter

1. Structural
2. Thermal comfort, ventilation and air quality
3. Daylighting
4. Cost
5. Sustainability

1	UN Habitat
2	IOM
3	ACTED
4	CESVI
5	CRS
6	Hands
7	PREPARED
8	SEAD Foundation
9	Sangtani

Table 10 - Key informant interviews - Shelter agencies

- **Codes and guidance**
  * Review of local design codes to assess their applicability and magnitude of wind loading in the area
  * Review of technical guidance available to shelter agencies at the time of response (Shelter Cluster Pakistan 2012, UN-HABITAT 2015)
- **Foundation capacity**
  * High level review of soils in the area.
  * Assessment of depth and width under normal and flood conditions.
  * Impact of platforms (made ground) on founding level
- **Wall capacity**
  * Check of wall capacity under steel roof beams supporting a saturated roof where no lintel or spreader beam present. This was in response to reports of saturated roofs causing walls to fail (Heritage Foundation 2013)
  * Slenderness, opening sizes and spacing
- **Roof capacity**
  * Size and spacing of beams in timber, steel and bamboo
  * Additional load from saturation and people (refuge) and wind uplift.
- **Connection details**
- **Stability**

Table 11 - Structural analysis

Structural

The purpose of the structural analysis desk study was to evaluate shelter against the material quality, stability and integrity indicators and to substantiate the associated metrics.

The study extracted relevant data sets from the shelter assessments and compared it to guidance available to agencies at the time, as reported by the end user group during in country consultations, in order to determine how well the guidance was adhered to. Reference was then made to relevant international best practice. Basic calculations and rules of thumb were carried out to assess the structural capacity of individual building elements including foundations, walls, openings within walls, roofs and key connection details, see table 11 for a full list of checks conducted. Whilst outside of the scope of the study, high level investigation into seismic hazard was included.

Design Information

Preliminary analysis of shelter assessments indicated that omission of basic construction detailing such as ring beams and lintels was widespread (see section 6.2). As both details are often hidden by plaster these findings were treated with caution. A finished building is a product of design (typically communicated through drawings), materials (and specification) and workmanship (https://www.designingbuildings.co.uk/wiki/Defects_in_construction). When undertaking a visual inspection it is not usually possible to identify which is the cause of a defect. However for details such as ring beams and lintels to be built it is reasonable to first check that they are included in design information.

The purpose of the review was therefore to evaluate shelter design information on paper. Subsequently this informed the development of a communication variable under the buildability, maintenance and modification indicator.

A total of 28 separate sets of design drawings from 9 different implementing partners were available. Agencies had an average of three different designs and a maximum of six, indicative of the varied design approaches taken and the need for design flexibility across the study area. The intention was to include three drawing sets for each of the five typologies but for concrete and layered mud typologies only one drawing set was available. 11 drawing sets were selected from 11 different agencies to cover each of the five material typologies (see table 12).

The review was split into four main sections, completeness of drawings, adequate specification of materials, adequate detailing and inclusion of Disaster Risk Reduction (DRR) features. Each of these sections was broken down into a yes/no checklist (see table 13) generating a score for each drawing review (Refer to Appendix F for summary of results).

This checklist provides a template against which shelters could be designed, checked or reviewed by agencies or others in the case that they fall outside of the scope of the **shelter guide**.

Agency	Implementing partner	Wall Typology
ACTED	ACTED	Loh-kat
CRS	PREPARED	Loh-kat
GIZ		Concrete block
UNHCR	HANDS	Fired brick
PREPARED	PREPARED	Adobe and Fired brick lower wall
Qatar charity		Fired brick
Concern	Indus resource centre	Adobe and Fired brick lower wall
Concern	BSDSB	Loh-kat
Concern	CESVI	Fired brick
IOM	Heritage Foundation	Layered mud/abode

Table 12 - Design information review input data

Drawing information/ Completeness	How many drawings are there?
	Which drawings have been drawn? (y/n)
	Are there sufficient dimensions to build the shelter? (y/n)
	What is missing? (E.g. window setting out, roof thickness and build-up)
Material specification	Are material types stated? (y/n)
	Are material strengths stated? (y/n)
	Is any other material information stated? (y/n)
Detailing	Is there a ring beam drawn? (y/n)
	Is the ring beam buildable from drawing? (Materials, dimensions, locations)
	Are there lintels drawn? (y/n)
	Are the lintels buildable from drawings? (Materials, dimensions, location)
	Is a corner connection shown? (y/n)
	Are there connections between roof and wall? (y/n)
	Are the connections buildable from the drawings? (Materials, dimensions, location)
	Are there connections between roof (and wall in the case of loh-kat) members? (y/n)
	Are the connections buildable from the drawings? (y/n) (Materials, dimensions, location)
	Is there redundancy? (y/n)
DRR	Is there an elevated ground (platform)? (y/n)
	Is there a raise floor level (plinth)? (y/n)
	What is the shelters capacity to withstand immersion and rainfall?
	Does the shelter allow for drainage at roof level? (y/n) (ie sloping roof)
	Does the shelter allow for drainage at base level? (y/n) (eg channels, sloping base)
	Does the roof overhang? (y/n)
	Any reference to previous flood height?
Other criteria observations (ventilators, two means of escape, vector control, flue?)	

Table 13 - Design information review check list

Thermal Comfort, Ventilation and Air quality

The purpose of the analysis was to evaluate the performance of shelter and develop metrics for thermal comfort, ventilation and air quality variables. Thermal comfort and air quality are both inextricably linked to ventilation and all three were considered within the same simple dynamic thermal analysis. Whilst the input data was consistent, the results were interpreted differently for each of the variables.

Survey data was reviewed to evaluate how existing shelter were performing. This evaluation compared the difference between external shade air temperature and internal air temperature (see table X for definitions of key terminology14

A basic computer model was built using IES software (https://www.iesve.com/software/ve-for-engineers) based on data geometry and material data from shelter assessments. The model was analysed against weather data obtained from Meteonorm[1] (http://www.meteonorm.com/) and then compared to and calibrated against readings taken during the shelter assessments. Once the model had been calibrated the relative impact of different design modifications (see section 7.1) on performance were explored.

1 *Meteonorm is a weather database and simulation platform that generates accurate and representative typical weather years for any place on earth. The database consists of more than 8 000 weather stations, five geostationary satellites and a globally calibrated aerosol climatology.*

Air Temperature (dry bulb temperature) is the ambient temperature of the air shielded from radiation and moisture and in this report will be given in degrees Celsius (°C). Internal air temperature is a function of the external air temperature, the surface temperature and therefore material and thickness of construction, and rate of ventilation.

Operative temperature (resultant temperature or dry resultant temperature) is a measure of thermal comfort derived from air temperature, mean radiant temperature and air speed. This variable can be calculated within the analysis models undertaken in this study however due to the limited survey data it could not be calculated for the survey data.

Relative humidity is a ratio written as a percentage of the amount of moisture contained within the air for a given temperature compared to the amount that would be present if the air was fully saturated at the same temperature (100% RH, also known as the dew point). Relative humidity is a function of both the moisture content and temperature, with the saturation point varying with temperature (warmer air can contain more moisture before saturation than cooler air).

Table 14 Thermal analysis definitions

Thermal model assumptions and input data:

- Geometry (plan, height, door and window opening dimensions) and material data were extracted from the shelter assessments
- Survey data that was collected:
  * Air temperature inside and outside (shaded)
  * Relative humidity inside and outside
  * Surface temperatures of walls
  * Ventilator opening widths, height and location in wall
  * Comfort opinions
  * Wall thicknesses
  * Roof construction

Climate conditions:

- The model was run based upon data for Nawabshah (See section 4.2 - Daylighting study)
- The expected climate change temperature increase in Pakistan as a whole is higher than the expected global average increase. Temperature increases of 1.4-3.7°C by 2060 with warming being more rapid in the southern and coastal zones.

Performance criteria

- The analysis model was run between the months of April and July for the hours of 9am to 6pm with internal air temperatures and operative temperature compared to external shade temperatures. Without mechanical cooling the air temperature in a shelter will at best match the external temperature in the shade. Where the surface temperatures of a shelter (roof, walls, floor) are below the air temperature they serve to reduce the operative (felt) temperature in the shelter.

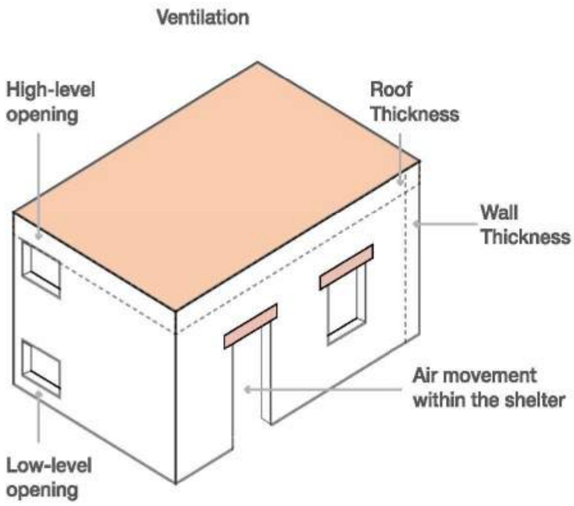


Figure 10 - Sketch showing factors effecting comfort and ventilation of the shelters and their design.

Daylighting

The purpose of the daylighting desk study was to evaluate natural light in shelter typologies and substantiate the lighting variable.

Opinions on lighting were gathered through the homeowner surveys. A computer daylight model was built based on data gathered from shelter assessments to test performance against criteria determined from industry guidance and explore the relative impacts of different design adjustments.

Daylight model assumptions and inputs:

Climate conditions:

- A review of weather data for the study area obtained from Meteonorm, showed that there are two distinct climates:
  - Southern Sindh – July/August rainy season with clear skies the rest of the year – reference file for daylight model: Pangrio
  - Sukkur and around – Predominantly dry with clear skies throughout the year – reference file for daylight model: Nawabshah

Performance criteria:

- The model was run for both locations between 9am and 5pm each day over the course of a year recording the percentage of shelter area achieving a useful daylight illuminance level of between 100 and 2000 lux. The two boundary levels have been chosen in agreement with scientific literature (Reinhart, C et al. 2013), with levels lower than 100 lux representing dark lighting conditions and values higher than 2000 lux representing bright lighting conditions associated with unwanted solar gains.

Shelter dimensions and arrangement:

- Daylight analysis models were built assuming average plan dimensions from shelter assessments.
- Windows were modelled as 0.6 x 0.9m with a wall thickness of 0.3m, representing the maximum size from the shelter assessments. Where a Jali screen was modelled this was assumed to be the full depth of the wall.
- Openings were assumed to be unobstructed externally with shelter assessments indicating that they are typically located in clearings in low density single storey clusters.
- Windows were assumed to face south because they model a condition that excludes direct solar penetration. Orientation of windows south or north is recommended to avoid solar gains.
- Interior surface reflectance was determined from material and colour data collected in the shelter assessments. (See table 15)

Component	Observations	Reflectance
Floor	The materials used for the floor vary between mud, combinations of mud and other materials such as straw and occasionally concrete. From visual comparison between the colour charts and the floor materials, the typical reflectance value is	~ 35%.
Walls	Walls painted in white colour:	~ 70%
	Materials light in colour such as adobe or layered mud:	~ 50%
	Materials dark in colour such as burnt bricks:	~ 30%
Ceiling	The typical ceiling in-fill material is reed matting 'chicks', which has a reflectance value of	~ 50%
	Sometimes terracotta tiles or darker timber is used:	~ 30%

Table 15 - Interior surface reflectance

Cost

The purpose of the cost desk study was to determine the cost of construction (materials and labour) and the lifecycle cost (operation and maintenance) in order to evaluate existing shelter and substantiate the cost indicator. Cost models were developed in line with best practice (R8ICS New Rules of Measurement) and fully detail the basis of assessment including assumptions, clarifications and exclusions.

To determine material costs, the design information (drawings and BoQs) for 16 shelter designs were analysed and compared. A BoQ for a concrete block shelter proved elusive and was improvised by substituting the wall and foundation material in a fired brick shelter design.

To facilitate direct comparison between the different designs, the BoQ's were sorted into common units (e.g. kg, m3) and then allocated to components (foundations, floor, walls, roof, windows and doors). Without a complete list of prices from the time of the response it was necessary to review and update them to give a fair comparison reflecting a consistent time period (2017). 2017 material costs were cross referenced against costs stated in the BoQ's themselves (where available), key informant interviews, existing studies (Global Shelter Cluster 2014) and high level data captured in the phase I database.

Labour costs were determined based on key informant interviews and design information (where itemised). This data was supplemented with questions on beneficiary contributions in the homeowner survey. Labour costs are considered less reliable than materials as less data was available.

Life cycle costs were judged to be a combination of maintenance costs, extracted from homeowner surveys, and a flat rate for electricity usage determined from homeowner surveys applied to all typologies. The design life for different shelter typologies were extracted from key informant interviews.

Sustainability

The purpose of the sustainability study was to evaluate shelter against the local supply chain and natural resources indicators and to substantiate the associated metrics.

The field surveys and key informant interviews provided the input data for material availability, labour standards, embodied carbon and recycled/reused.

To determine the embodied carbon of shelter designs, material quantities from the cost analysis (see section 4.2 – Cost analysis) were multiplied by carbon factors (kgCO2/kg of material) which were developed for both production and transport. Factors for material production (raw material extraction and manufacturing) were gathered from a range of industry sources, with no one source covering all of the materials included, they are listed and discussed in Table 16. They predominantly result from studies in Europe and North America, as equivalent recognised studies could not be found for the region. It is anticipated that where variations between the assumed and actual values occur they will likely be the result of less efficient industrial techniques and would therefore serve to increase the carbon factors.

Transport factors were developed based on the mode of transport and distance travelled for two journey legs. The first leg covered point of origin, such as a factory in Karachi or a forest in Punjab, to a merchant or warehouse, which for this study was assumed to be located in Shikarpur. The second leg consisted of a shorter journey from the merchant to a village, most likely via a different mode of transport. Distances and modes of transport for the first leg were estimated based on research into the most likely locations for sourcing a given material. Transport modes for the second leg of the journey were developed based on homeowner surveys. For distance a worst case (90th percentile) of 20km was assumed. Values for vehicle emissions were extracted from data sources in table 16 below.

Figure 11 - Material transportation assumptions

Key:

Point of material origin

Warehouse/merchant

Journey 1 – Point of origin to warehouse/merchant in Shikarpur

Journey 2 – Shikarpur to village (20km)

Carbon factor source	Comments
ICE (Inventory of Carbon and Energy) database	Developed by the University of Bath, in partnership with the Carbon Trust. Regarded as an industry-leading embodied carbon resource. This study refers to the updated version 2.0 of the database, from January 2011
UK government greenhouse gas database	UK-focussed but globally applicable for the production of many material types. This study refers to the version of the database dated 2016
Winnipeg emissions factors database	North America-focussed but globally applicable for many material types. This study refers to the version of the database dated 2012
Various sources indicating likely manufacturing processes and locations in Pakistan	Refer to Appendix F for more details

Table 16 - Carbon factor sources


8
4

4.3 Physical testing

The purpose of physical testing was to evaluate the performance of existing shelter under simulated flooding and heavy rain, and substantiate the water resilience indicator. Phase I identified a number of flood (and heavy rain) resilient features (Section 4.3) which were subsequently captured as variables of water resilience: platforms and raised floors, waterproof materials, sacrificial protection, overhangs and drainage. The uptake of these features was explored by the field surveys, but findings on their effectiveness were limited by just 62 of the 800 shelters having been subjected to flooding since they were constructed.

Early engagement with the TAG during the planning of the physical testing highlighted that limited budgets may preclude a fully flood resistant design and that understanding the relative value of smaller interventions would be key. Also the need to distinguish between the impact of and measures to mitigate against standing water and heavy rain. The following requirements were determined:

Credible testing partners and test facilities with a view to setting up a local centre of knowledge with residual capacity to continue testing

An understanding of **flooding (and rain) hazard and resulting damage to shelter** (see section 2.2 and 2.3)

Reproducible and locally achievable **test designs** that simulate real construction as closely as possible. Subsequently developed and refined as follows:

- Exploration of the relative value of different DRR design features on vernacular construction inspired by designs observed in the field and including known poor construction as a 'base case' for comparison. Designs will include incremental changes to enable comparison between them with inclusion of at least one design representing best practice.
- Separate rain and standing water tests to differentiate the effects of each and identify where efforts should be focused
- Full scale test panels and materials and labour imported from the study area to simulate conditions in the flood affected areas

Credible testing partners

NED University in Karachi were appointed on the basis that they had experience of full scale vernacular construction testing, rain and flood modelling expertise, material testing equipment and were located in close proximity to the study area enabling materials and labour to be brought in, replicating conditions in the field.

With no existing facility available to conduct full scale flood and rain tests it was necessary to design and build the facility as well as the test panels themselves, leaving behind a testing centre that can continue research. The physical testing was a collaboration between IOM, Arup and NED, with NED taking responsibility for design and construction of the facility which was located on their campus, IOM oversaw construction of test panels including sourcing of materials and labour, and Arup led the design of the tests themselves, with input and review from NED and IOM. For construction of the panels IOM appointed a local NGO with training and experience of lime construction, with oversight provided by an IOM shelter advisor.

Heavy rain test design

The purpose of the heavy rain testing was to:

- To measure relative performance of improved vernacular construction (adobe and loh-kat) to heavy rain
- To simulate the damage caused by rainfall during the 2011 monsoon in order to compare to that caused by standing water.

Test conditions

Tests were conducted in two batches of six panels over the course of one day. Rain tests were based upon data gathered by NED from the Pakistan Meteorological Department for Tando Ghulam Ali which on August 11th 2011 saw 13.7 inches of rain, the highest in Sindh since 1931. Each panel was subject to the same conditions with wind driven rain was simulated by inclining the sprinklers at an angle to the wall panels, ensuring that the full height of the panel was wetted. The sprinklers were calibrated by placing measuring cups on the ground to ensure that the design conditions were achieved. Tarpaulin was erected to shield the sprinklers from any wind on the day. The backs of the panels (inside of shelter) were kept dry. Drainage was provided at the base of each panel to prevent standing water.

Observations and equipment

An observation and measurement regime was designed to document the testing:

Full photographic record, photos taken from fixed location, minimum of one per panel every 30mins, additional photos of points of interest as required.

Water run off for each panel was channelled separately through a filter which captured eroded material, enabling measurement of volume at the end of the test.

Standing water test design

The purpose of the standing water testing was:

To measure the relative value of different DRR measures for resisting standing water effects on foundations and base of wall.

To measure movement and damage over time (culminating in time to collapse) due to standing water

Test conditions

Flood test conditions were based upon data gathered from homeowner surveys, suggesting an average flood depth and duration of 4' for 10 weeks. It was decided that the flood profile (depth over time) should reflect anecdotal evidence from shelter agencies supported by research papers that water levels rose quickly and then took a number of weeks to drain away. It was thought that the effectiveness of raised floors and toes would require the water level to be below their high point whilst this flood profile would quickly inundate them, limiting the data which would be collected on their value. This led to a two stage flood profile, with the water level rising to 2' and then to 4' later on, all within the 10 week testing period (See Figure 13). Water was pumped into the tank and drained at the rates provided below in a way that prevented the panels being subject to flowing water.

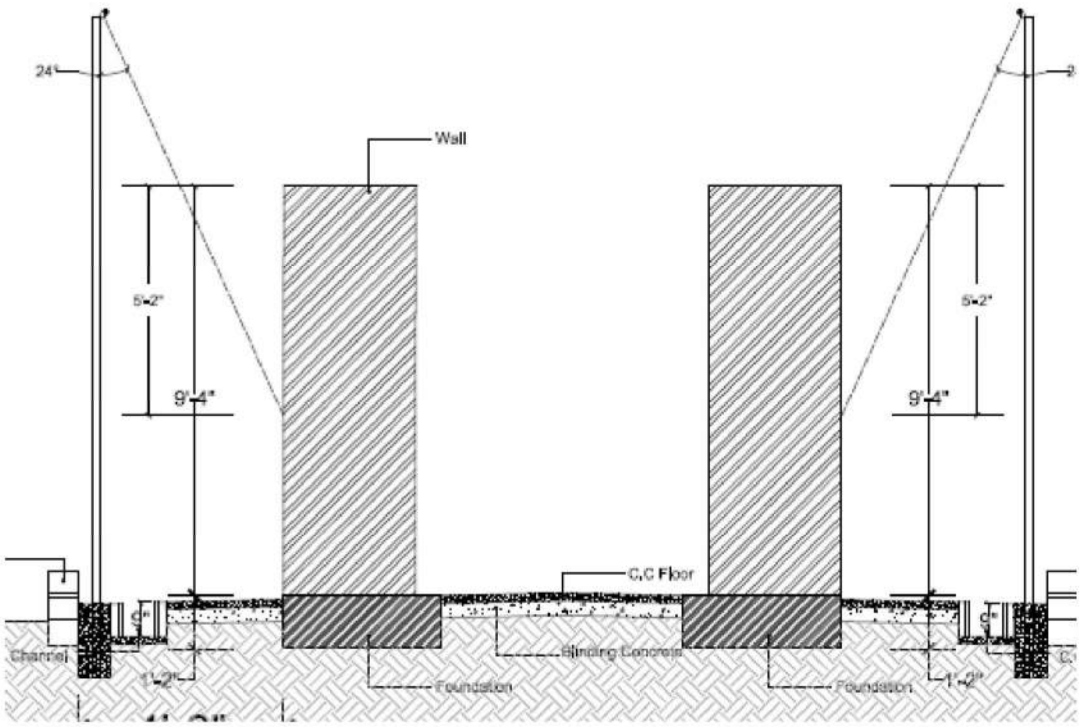
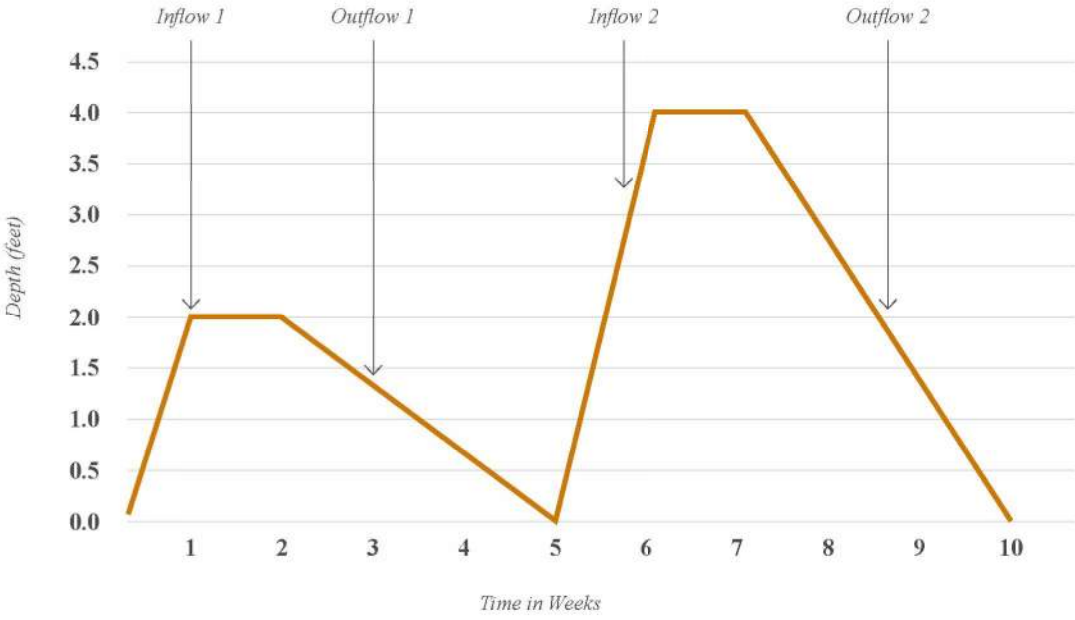


Figure 12 - Section showing two rain test panels with sprinkler and drainage arrangement



Inflow 1	Outflow 1	Inflow 2	Outflow 2
0.286 feet per day	0.095 feet per day	0.571 feet per day	0.190 feet per day

Figure 13 - Flood testing profile – water depth over time and flow

Observations and equipment

The following observation and measurement regime was designed to capture testing:

- Total station[2] measurements were taken once a day from fixed locations to record any movement in the panels over time
- Still photos were taken once a day from brackets fixed to the tank wall to ensure that locations and framing were consistent. Frequency was increased as required when panels began to show signs of distress.
- Two live feed security cameras were set up to record live video footage of the entire tank from two different angles. This ensured that the point of failure was captured regardless of when it occurred, as full time supervision would have been impractical. A web interface enabled remote monitoring from the team in the UK.
- A drone was used to capture additional stills and video footage.

2 A total station is a computer mounted on a tripod which is used for surveying

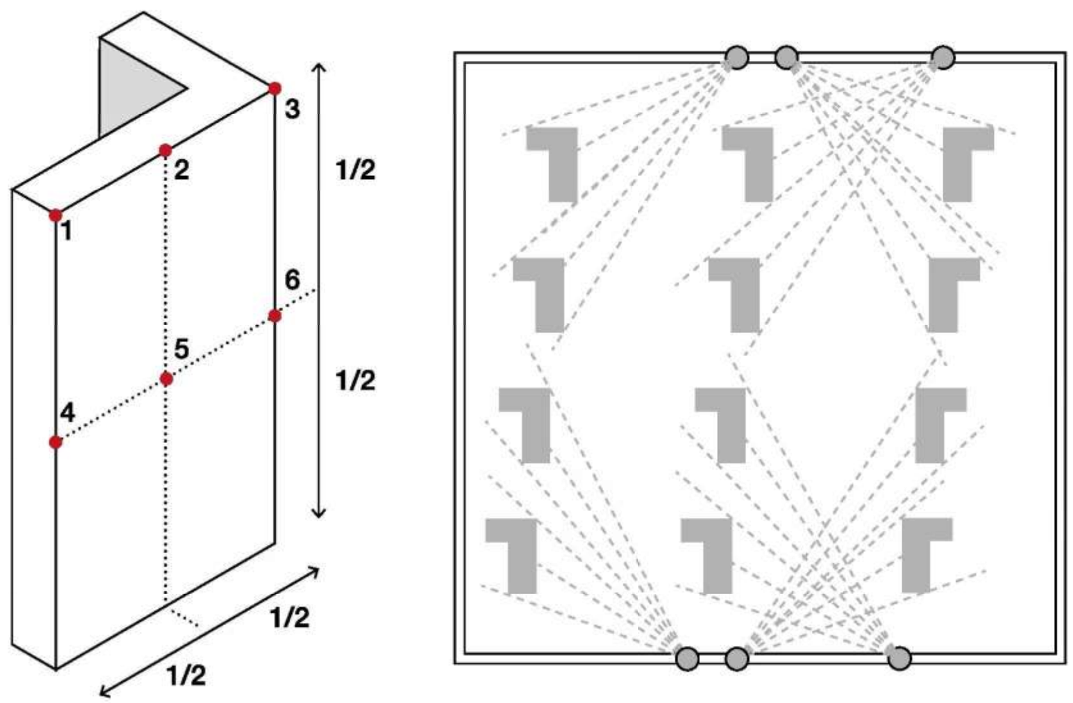


Figure 14 - Total station measurement points on panels, fixed still photos and camera mounts

Age of construction: The panels tested were newly constructed and as such will not have been subject to usual wear and tear that gradually degrades a building. Nor will they have been modified by homeowners.

Wall panel's vs entire shelter: The scope of testing was restricted by the time, budget and space available. Opting to test wall panels in place of entire shelters allowed more tests to be carried out, unfortunately this excludes exploring the relative value of design features such as ring beams and adequate tie-ing of the roof structure, which are known to improve a buildings stability.

Materials: Similarly, it was necessary to narrow the number of materials explored. Concrete block was excluded based on limited occurrence before and after flooding (see section 2.1 – typologies). Flood damage studies (UN-HABITAT 2012) had already recorded that loh-kat can be flood resilient as the timber lattice is able to remain in place and continue to support the roof after the mud plaster has been washed away. Adobe and layered mud walls constitute the same or very similar materials fabricated through different processes and results from one will enable findings to be extruded for both. The focus of the flood testing was therefore adobe, whilst rain tests looked at both adobe and loh-kat.

Wind: Wind serves to drive rain at an angle to wall surfaces, serving to undercut protective roof overhangs and erode the wall surface. To simulate wind at a constant speed for the rain tests would require a wind tunnel, and is out of the reach of this project. This was approximated by angling the sprinklers instead

Flowing water: Flowing water will subject shelter to considerable dynamic pressures and erosion which are considered beyond reasonable design performance of vernacular construction whilst simulation and monitoring of consistent water flow against 12 panels would require a specialist facility. Designing low cost vernacular construction to withstand standing water is a significant challenge and testing for standing water alone improves replicability of the results and clarity of conclusions.

Ground compaction: The ground around the panel foundations was compacted by hand after the panels were completed and will be less dense than typical. It is likely that standing water will have infiltrated faster as a result, potentially influencing the speed with which unstabilised earth foundations failed.

Soil type: Composition of soil varies from one location to another and as a result are more or less suited to stabilisation with lime or cement and earth construction in general. The test results will be representative of the performance of the soil which was imported from the study area.

Table 17 - Physical testing key limitations

5
Key Findings

This section substantiates and explains the qualitative and quantitate metrics that were used to evaluate shelter and details the findings in line with the three key criteria, refer to the Appendix B for a tabular summary.

1. Safe and Resilient
2. Acceptable to Cccupant
3. Sustainable

The findings are based on data gathered in the field, physical testing and analytical desk studies. Where the wall typology is thought to influence the findings a simple ranking is provided. A rank of 5 means that typology was judged to give the best performance for a given metric relative to the other typologies. The rankings are simple in that they provide comparison by placing them in order only and are not weighted, e.g. they illustrate that loh-kat performs better than fired brick, but not by how much. Weighting was purposefully avoided due to the complexity of such an undertaking and critically, the inherent subjectivity that this would introduce. In contrast simple rankings invite the reader to assign their own weighting in line with the stated project aim of informed decision making.

The ranks given in this report portray what was found in the field, they are different to the scores given in the shelter guide which represent the full potential of the materials in line with the recommended designs.

Where wall typology is thought to affect performance, ranks are provided at the start of each section in the margin. A full break down of the derivation of the rankings is provided on the following page. Where a variable was felt to be unrelated to the wall typology it was awarded an 'x'.

The table below presents average ranks for each of the wall typologies for the three key criteria revealing that adobe and layered mud perform well throughout and achieve the best ranking overall. Fired brick performs strongly under safe and resilient and acceptability criteria, but receives the lowest rank for sustainability. Loh-kat mirrors fired brick with an almost equal and opposite performance, doing poorly for safe and resilient and acceptable to occupant, and receiving the highest average rank for sustainability. Concrete block follows a similar pattern to fired brick, although its rarity meant that it was not possible to sample a statistically representative sample and it should be treated with caution.

Wall typology	Loh-kat	Layered mud	Adobe	Fired brick	(Concrete block)
Safe and Resilient	3.2	3.8	3.8	4.0	(4.5)
Beneficiary Acceptability	2.9	4.0	3.7	4.7	(4.4)
Sustainable	4.7	4.5	4.5	1.7	(2.5)
Total	**3.4**	**4.0**	**3.9**	**3.7**	**(4.1)**

Table 18 - Average rankings for wall typologies against each of the key criteria

Criteria	Indicator	Variable	Loh-kat	Layered mud	Adobe	Burnt brick	Concrete block
Safe and Resilient Material quality	Material quality	Compatibility	5	5	5	1	5
		Durability	1	3	3	5	5
		Strength	1	3	4	5	55
	Stability and Integrity	Foundation depth	5	5	5	5	5
		Foundation width	5	5	5	5	5
		Stability and slenderness	1	2	3	5	4
		Openings	x	4	4	5	4
		Connections and tying	x	x	x	x	x
		Roof capacity	x	x	x	x	x
	Water resilience	Elevated ground	x	x	x	x	x
		Raised floor	x	x	x	x	x
		Waterproof materials	3	3	3	5	5
		Sacrificial protection	x	x	x	x	x
		Overhangs	x	x	x	x	x
		Drainage	x	x	x	x	x
	Buildability, maintenance and modification	Communication	x	x	x	x	x
		Buildability	5	3	1	4	No data
		Tools	x	x	x	x	x
		Skills availability	5	3	3	1	1
		Training	1	5	5	2	5
		Maintenance	1	3	3	4	5
		Modification	x	x	x	x	x
Acceptability	Comfort	Thermal Comfort	5	5	5	5	5
		Ventilation	5	5	5	5	5
		Lighting	x	x	x	x	x
		Waterproofing	x	x	x	x	x
	Space	Size	5	1	3	3	4
		Layout and flexibility	x	x	x	x	x
	Protection	Security	1	3	3	5	4
		Privacy	1	4	2	5	4
	Health & Safety	Internal air quality	x	x	x	x	x
		Fire Hazards	1	5	5	5	5
		Vector Control	2	5	3	5	4
Sustainability Cost	Cost	Materials	5	4	4	2	2
		Labour	5	5	5	2	No data
		Life cycle	x	x	x	x	No data
	Local Supply chain	Availability of materials	3	5	5	2	1
		Labour standards	5	5	5	1	5
	Natural resources	Recycled/ Reused	x	x	x	x	x
		Embodied Carbon	5	4	4	1	2

Table 19 - Full break down of wall typology ranks against key criteria

6 Safe and Resilient

6.1 Material Quality

Compatibility

Materials used for foundations, walls and roof should have compatible strength and water resilience so as to avoid undermining the performance of the shelter. The foundations should be at least as strong and waterproof as the walls that they support and masonry should be bonded together with comparative mortar. Generally, the surveys suggest that the wall and foundation materials used are compatible.

A minority (12%) of burnt brick shelters had unstabilised mud foundations, and a similar percentage used unstabilised mud mortar. In both cases the lesser properties of unstabilised mud are serving to undermine the performance of, and to negate the investment in the fired bricks. This was demonstrated by physical testing where a fired brick and mud mortar wall panel failed at a standing water depth of just 7inches.

The survey data (figure 15) shows that whilst there is variation across the materials used for wall construction (layered mud, adobe, fired brick, loh-kat), there is less when it comes to foundation (mud or burnt brick) and roof construction. Nearly all roof coverings consisted of layers of mud, plastic and chicks and nearly all were supported by secondary beams made of bamboo with primary structure made of steel, bamboo or timber.

Durability is a key concern for homeowners and a key differentiator between the wall typologies. Natural materials such as earth and timber require careful detailing to protect them against water damage. A review of loh-kat foundation details suggests that there is room for improvement in this regard, with recommended details provided in the shelter guide.

The main durability concern for roofing was insect attack of timber and bamboo, affecting 21% of shelters. This is unsurprising given that the commonly used treatments observed in shelter and reported by agencies (i.e. oil, red oxide paint, grease and lime) are known to be ineffective and may result in a life span of less than one year (Kaminski, S et al. 2016).

Key informant interviews asked shelter agencies the anticipated life spans of different shelters with a range of values given. This illustrates the difficulty of predicting life spans, whilst the data also indicates low expectations across the typologies with adobe and layered mud in some cases given a similarly very low prognosis to loh-kat. The engineering judgement column is based upon an upper and lower bound of what should be possible to achieve based on the inherent characteristics of the materials. The upper bound represents a shelter that is well designed, detailed, constructed and maintained, the lower bound represents the opposite. It is possible for earth construction to be as durable as engineered materials such as fired brick if its limitations are understood and mitigated, refer to section 6.3 Water Resilience for more detail.

Loh Kat	5
Layered mud	5
Adobe	5
Concrete Block	5
Fired Brick	1

Wall Topology Rank
Compatibility

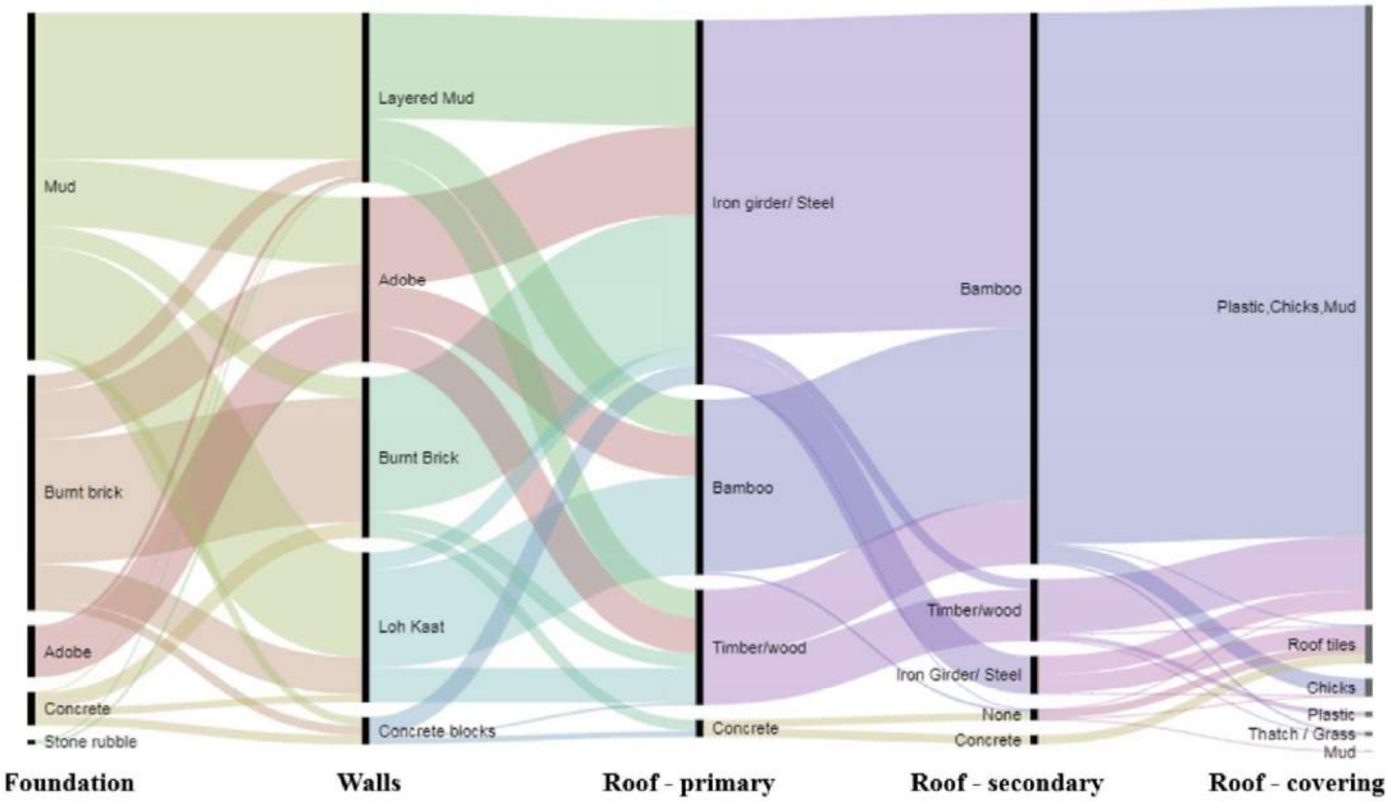


Figure 15 - Ribbon diagram illustrates which materials were used for foundations, walls and roofing and how often they were used together. For example adobe block foundations were used with adobe walls and a very small number of layered mud walls.

Durability

Durability is a key concern for homeowners and a key differentiator between the wall typologies. Natural materials such as earth and timber require careful detailing to protect them against water damage. A review of loh-kat foundation details suggests that there is room for improvement in this regard, with recommended details provided in the shelter guide.

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Wall type	Rank
Concrete Block	5
Fired Brick	5
Adobe	3
Layered mud	3
Loh Kat	1

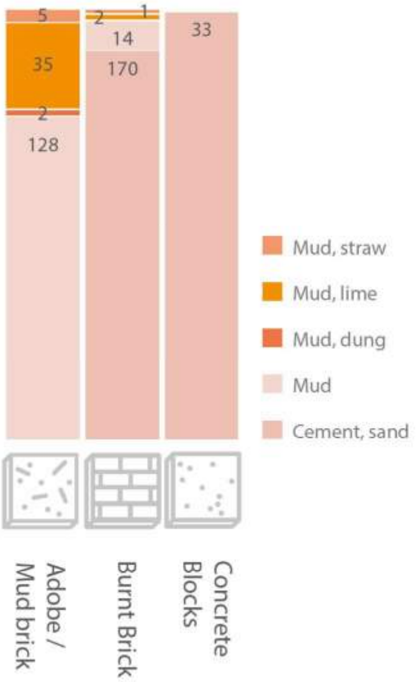
Wall Topology Rank
Durability

Wall typology	From Key informant interview	Engineering judgement	
		Lower	Upper
Loh-kat	1 to 7	1	15
Layered mud	2 to 8	5	50
Adobe	2 to 8	5	50
Fired brick	7 to 15	10	50
Concrete block	No data	10	50

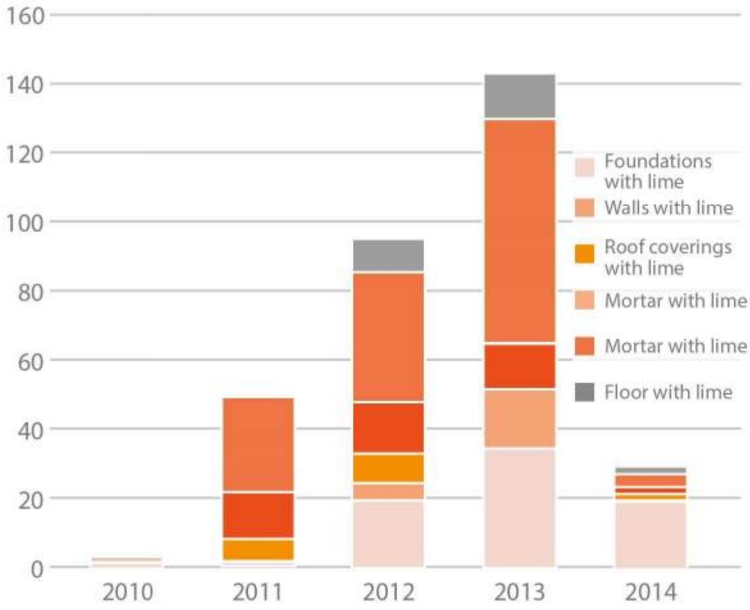
Table 20 - Shelter design life (years)

Material quality

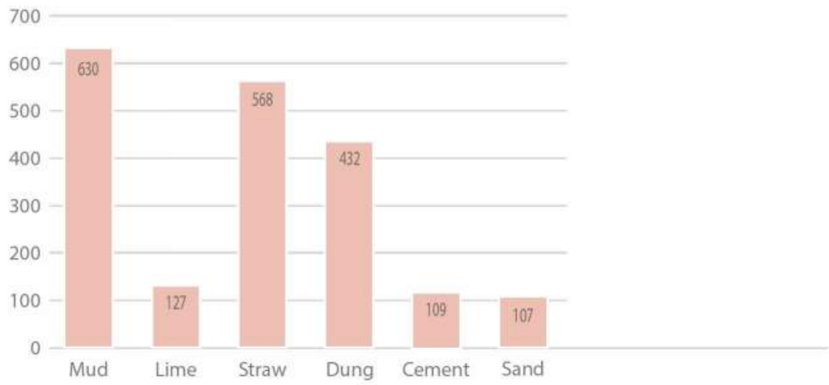
Mortar material



Where and when lime was most commonly used



Plaster material

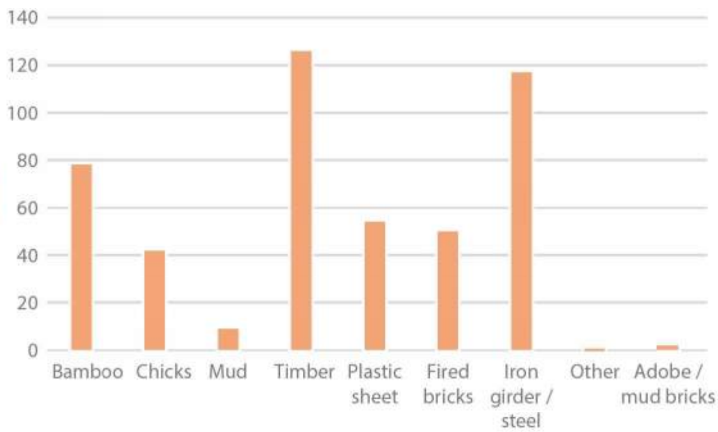


28%

of the buildings built between 2010 and 2014 used lime

Did people have any concerns about material quality?

Materials that people had concerns about quality



Specification

Materials should be adequately specified to maximise their design life. Quality should be checked at point of procurement, delivery and use to ensure that the specification is being adhered to so that substandard materials are caught.

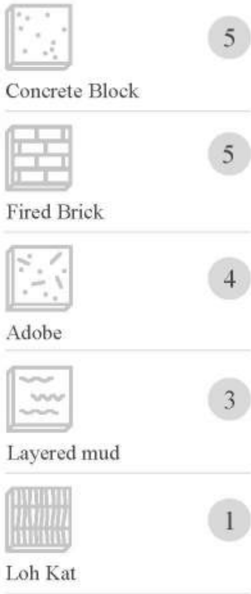
Quality of timber and steel were the key concern for homeowners, followed by bamboo, affecting roofing and loh-kat walling. Whilst agencies reported concerns over soil salinity affecting quality of earth this was not picked up by the surveys, indicating that the issue was not understood or captured in the forms, it was resolved by agencies or else over reported.

Agencies reported that quality of bamboo decreased over time, with farmers responding to a surge in demand by over fertilising bamboo so that it matures in one year rather than three. Other issues include excessive lack of straightness for poplar which is possibly due to being air rather than kiln dried.

Whilst compressive strength is a key consideration for loadbearing construction such as adobe, layered mud, concrete block and fired brick a single storey shelter places light demands on the walls, with 2.5N/mm2 required for such structures by building codes in countries such as Uganda and Tanzania. Where masonry is to resist seismic loads strength becomes more important and values of twice this might be recommended.

In practice it is unlikely that this data will be readily available or easily determinable in the field which is reflected perhaps by the fact that none of the agency designs included minimum material strengths. Low tech approximations of strength include dropping a brick from shoulder height to see if it breaks or not (Houben, H and Guillaud, H. 1994).

Compressive strength is roughly related to density, with compaction serving to increase the strength of soil construction. Layered mud tends to be less compacted than adobe blocks and so is often weaker, requiring thicker walls as a result. Stabilisation is another way to improve the strength of soil, with lime blocks tested by NED achieving up to 7N/mm2



Wall Topology Rank Specificiation

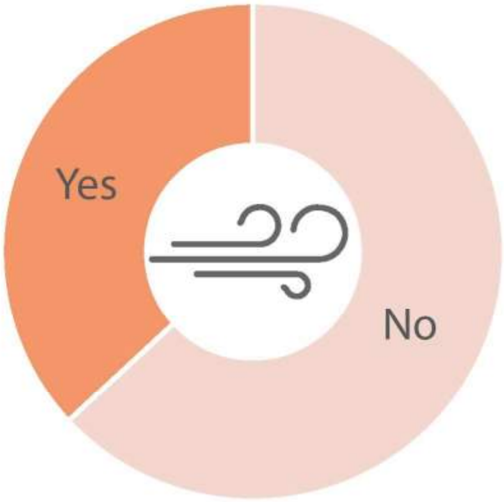
Type	Compressive strength (N/mm2)
Unstabilised earth	1.2 to 1.7
Cement stabilised earth	1.1 to 1.5
Lime stabilised earth	1.1 to 7
Fired bricks	10 to 13

Note: Tests conducted by NED based on sample size of at least three

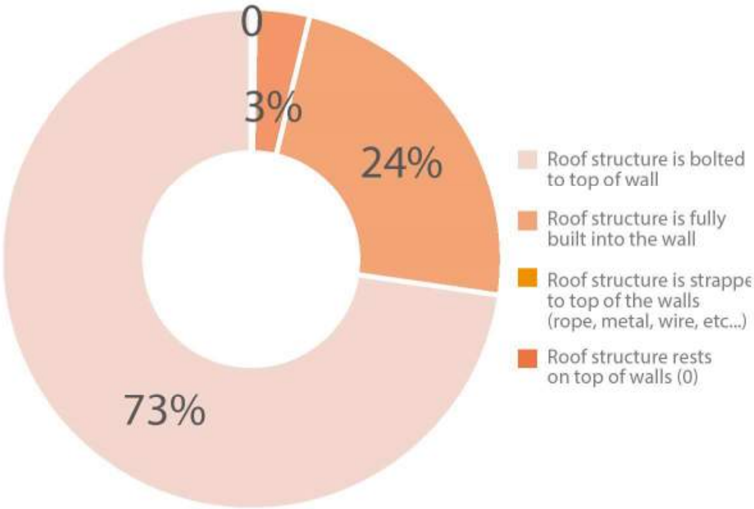
Table 21 - Brickblock compressive strength testing results

Stability and integrity

Has the roof ever lifted off during high winds?



Roof connection to wall

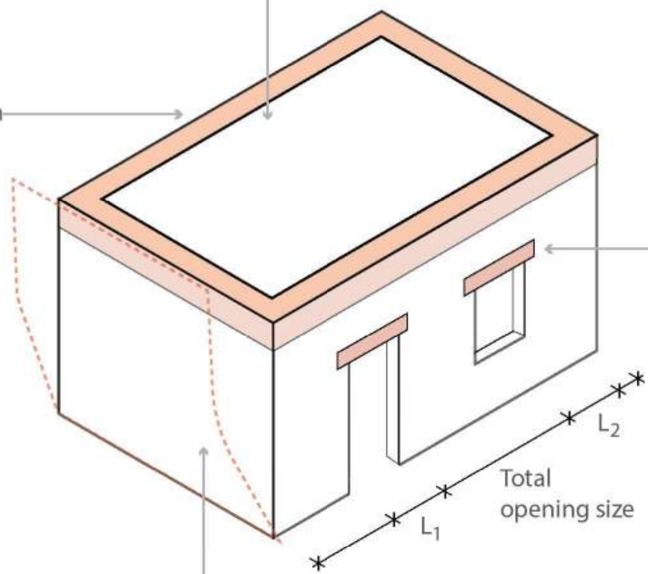


30% of drawings did not show a connection between the roof and walls

Percentage with a ringbeam

15% Field surveys

43% Drawing review



Percentage with a lintel

52% Field surveys

43% Drawing review

Percentage of walls with no tilting or bulging (%):

Adobe / Mud brick	Burnt Brick	Concrete Blocks	Layered Mud	Loh Kat
50	74	74	40	12

Percentage of walls meeting slenderness limits (%):

Adobe / Mud brick	Burnt Brick	Concrete Blocks	Layered Mud	Loh Kat
42	67	12	22	0

6.2 Stability and Integrity

Foundation depth

The required depth and breadth of foundations are a function of a buildings weight and the properties of the soil, the aim being to ensure that the building does not sink into the ground.

The surveys found an average foundation depth of 0.78m with no significant variation between the wall typologies. This exceeds the 0.6m minimum guidance provided in the shelter cluster guidelines, indicating that this guidance was adhered to. UN-Habitat guidance provided further detail suggesting a depth of 1.2m for soft soil, in the absence of guidance on how to determine hard vs soft soils this was not reflected in findings from the surveys.

In contrast to the field surveys the review of agency drawings found foundation depths for load bearing construction to range between 0.2m to 0.5m, whilst loh-kat was typically embedded 0.6m into the ground.

High level geotechnical analysis of the soils in the Sindh (refer to maps in Appendix C) suggest that 0.75m depth would be suitable for both drained (dry) conditions as well as for flooded (undrained conditions), providing flood resilience.

Where the surrounding ground level is artificially raised up the foundations should be embedded at 0.5m into the original ground level to avoid founding the shelter in soft ground which would have been placed by hand.

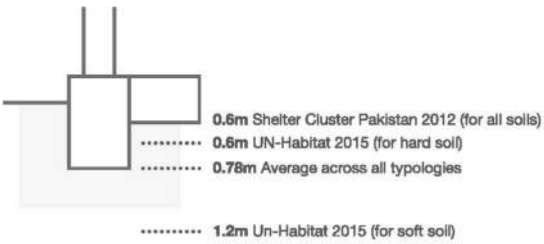


Figure 15 - Foundation depth

Foundation width

Foundations widths were found on average to be slightly less that the two times wall width advised by the shelter cluster for each of guidelines the wall typologies. High level geotechnical analysis would suggest that the 0.55m average is reasonable however.

Stability and slenderness

A key metric for the stability of load bearing construction are 'slenderness ratios'. As a wall is made longer or taller these ratios ensure that the wall thickness is increased by a commensurate amount to maintain stability. In seismic zones these ratios are typically adjusted to increase the wall thickness with the aim of improving stability under lateral earthquake loads.

Shelter cluster guidelines specified minimum thicknesses for wall typologies but did not give maximum lengths or heights, UN Habitat guidance went a step further by providing slenderness limits intended for moderate seismicity. Comparison with international benchmarks shows good agreement with the UN habitat guidance (See table 23). These limits were well adhered to by fired brick, less so by the other typologies.

Traditional loh-kat can provide a potentially stiff wall panel, as the woven interlocking timber branches prevent it from deforming. Bamboo framed loh-kat does not interlock and relies instead on f bracing and strong connections. With just 12% of loh-kat walls presenting no tilting or bulging it would suggest that bracing in walls and roof as well as adequate connections were often omitted.

Concrete Block	5
Fired Brick	5
Adobe	5
Layered mud	5
Loh Kat	5

Wall Topology Rank
Foundations

Fired Brick	5
Concrete Block	4
Adobe	3
Layered mud	2
Loh Kat	1

Wall Topology Rank
Stability

Wall material typology	Foundation width (m)	Foundation width (m) / wall width (m)
Adobe	0.6	1.8
Fired brick	0.5	1.9
Concrete block	0.6	3.3
Layered mud	0.6	1.8

Table 22 - Foundation width

Wall typology	Rank
Fired Brick	5
Concrete Block	4
Adobe	4
Layered mud	4
Loh Kat	*

Wall Topology Rank
Openings

* Not Applicable

Opening size and spacing

Openings act as weaknesses in loadbearing construction and should be sized and located to avoid compromising the strength and stability of the wall. Where the roof structure applies loads above or nearby to an opening, a lintel or equivalent is required. Survey data suggested that burnt brick performed best in this regard with 15% of shelter exceeding opening limits, whilst 35% to 40% of adobe, layered mud and concrete block were beyond the recommended limits. This guidance does not apply to Loh-kat construction as the structure is made up of a series of beams and columns.

Rules of thumb based on trial and error are available in guides and in some cases have been codified (See table 24). Guidance varies by material in order to account for differences in material properties. For example earth blocks are expected to be a lower strength material than fired brick, and so the size of openings is less and spacing between them is greater. The structural study shows that the limits given in the shelter cluster guidance are below best practice, but that the UN-Habitat guidance limits were about right.

		Slenderness h/t	Slenderness l/t	Reference
UN Habitat guidance	Adobe	8	14	Technical specification for Earthen Buildings in flood affected areas
	Layered mud	6.3	11.2	
	Fired brick	13.3	24	Technical specification for Masonry House in flood affected areas
	Concrete block	15	27	
Arup study	Adobe	8	20	Australian earth handbook
	Layered mud	6.3	10	Indian 'Improving earthquake resistance of earthen buildings' guide
	Fired brick	13.3		Indian 'Improving earthquake resistance of low-strength masonry buildings' guide
	Concrete block	13.3		

Table 23 - Slenderness limits

Connections and tying

Connections are required between the roof covering and the structure, between roof beam to roof beam and between the roof beams and tops of the walls. They serve to prevent the wind from lifting up the roof, with overhangs in particular being sensitive to uplift. The Pakistan Building Code recommends that a value of 2.5kpa for coastal and 1.6kpa for inland areas can be applied to an overhang when determining the load that connections must resist. Roof connections also make a valuable contribution to the seismic resilience of a shelter by transmitting load between walls. Critically this requires that roof structure must not be able to slide relative to other parts of the roof or the walls, requiring a stronger mechanical fixing than that required for wind uplift alone.

There is a potential conflict in situations where roofs should be demountable and appropriate connections will need to be designed for this purpose. This was anecdotally reported as a priority by some occupants with insecure land tenure who wished to be able to take their roof with them in case they moved.

Shelter assessments found that 73% of roof structures rest on top of the wall, without being fixed in place and that a third of all respondents reported that their roof had lifted off to some degree during high winds.

When mud roofs become waterlogged their weight increases, with this additional load cited as a cause of failure for some walls (UN-Habitat 2012, Heritage Foundation 2013). Hand calculations determined that this would only be an issue for very weak walls (<0.3N/mm2) and that this issue is easily solved by ensuring roof beams are supported by lintels or ring beams.

	Wall typology	Sum of opening sizes as % of wall (Max)	Minimum distance from corners (m)	Minimum distance from other openings (m)	Reference
Shelter cluster guidance	Adobe	50%	0.61	0.61	Shelter Cluster Pakistan Compendium of Key Documents
	Layered mud	50%	0.61	0.61	
	Fired brick	50%	0.61	0.61	
	Concrete block	50%	0.61	0.61	
UN-Habitat	Adobe	40%	1.22	1.22	Technical specification for Earthen Buildings in flood affected areas
	Layered mud	40%	1.22	1.22	
	Fired brick	42%	0.91	0.91	Technical specification for Masonry House in flood affected areas
	Concrete block	42%	0.91	0.91	
Arup study	Adobe	33%	0.75	1	From the Australian earth handbook
	Layered mud	40%	1.2	1.2	Indian 'Improving earthquake resistance of earthen buildings' guide
	Fired brick / Concrete block	42-55%	0.23-0.6	0.45-0.56	Indian 'Improving earthquake resistance of low-strength masonry buildings' guide

Table 24 - Opening size and spacing

Where loadbearing construction is used walls should be fully bonded at the corners and between leaves with regular 'headers'. Ring-beams should be included in order to tie the walls together. They can also serve to distribute load from the roof into the wall as well as to span over openings, respectively replacing both wall plates or spreader beams and lintels. As a minimum ring-beams should be included at roof level, and will provide additional seismic resistance if included at base and below windows (cill level).

Just 15% of shelters included a ring beam according to shelter assessments, and whilst this can be difficult to confirm via a visual survey as they can be hidden behind plaster this finding was lent additional weight by the design information review which found that less than half of the drawings for loadbearing construction included a ring-beam. Further to this just one drawing set indicted brick bonding, and more than two thirds omitted roof to wall connections.

Roof capacity

Roof structures should be designed and built to accommodate the self-weight of the roof under both dry and wet conditions, when it becomes heavier. It may also be desirable for the roof to act as a place of refuge in the case of a flood, in which case it will need to withstand the load applied by weight of people. With just 6% of shelters having flooded this is yet to be tested and just 4% reported having accessed their roof, mainly for sleeping.

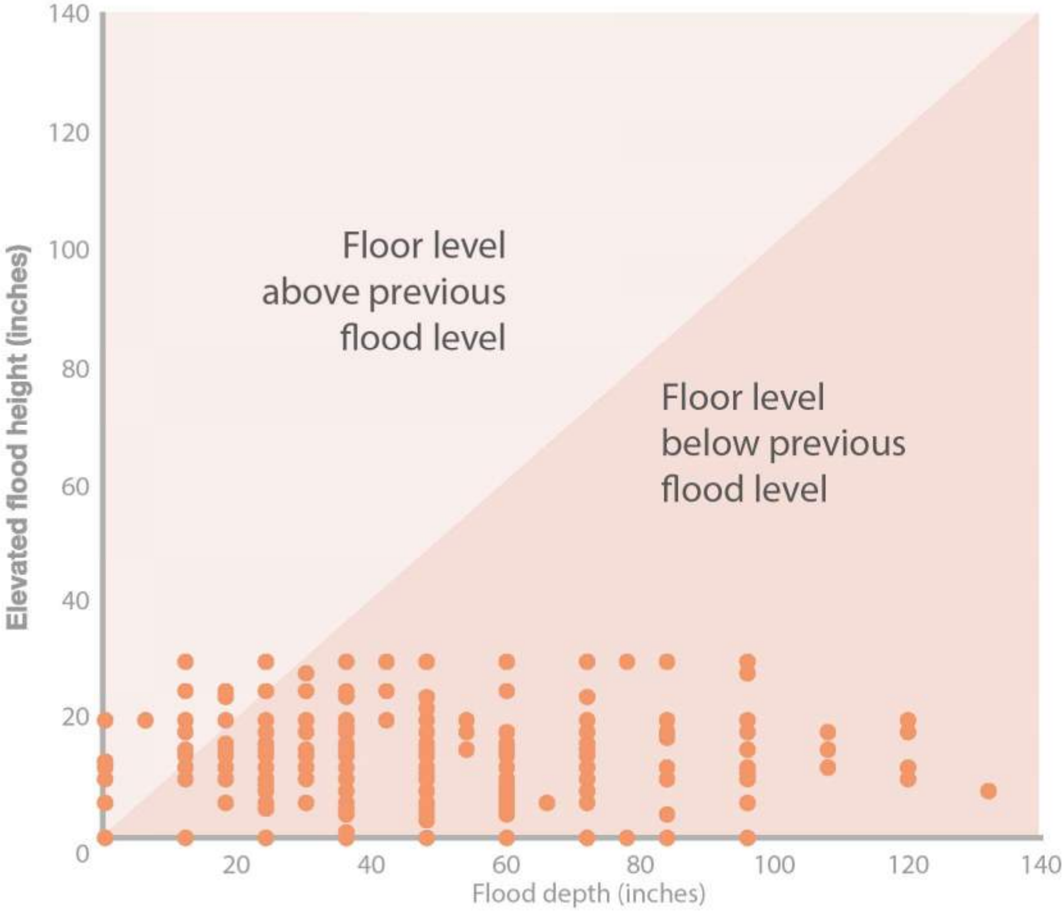
A saturated mud roof 100mm thick applies a 2.5kpa load, whilst a standard load for people to access a roof is 0.6kpa. The design information review suggested that mud roofs, where labelled, are built at ~50mm thick, this may then increase to 100mm over time as the homeowner adds layers to mud to maintain it.

Inspection of roof structure designs in the design information review suggest that steel beams would be adequate to carry the recommended loading, whilst bamboo roof structures may need reinforcement, none of the drawings reviewed included a timber roof.

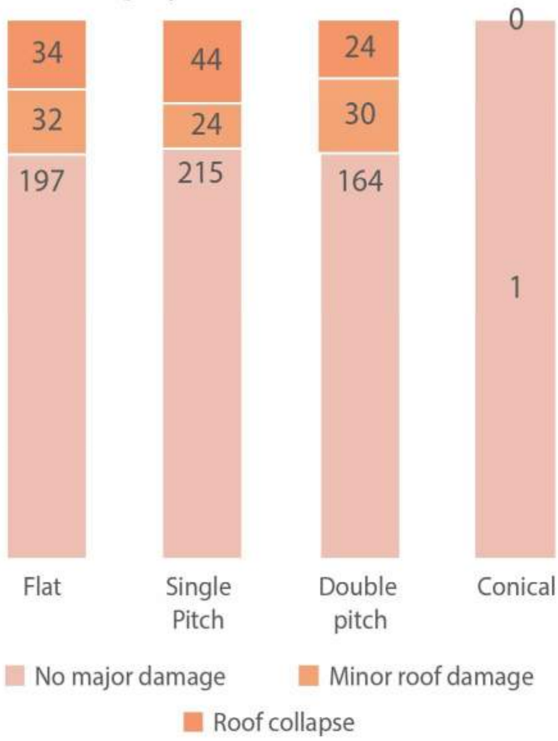
The capacity of a bamboo roof can be increased by simply increasing the amount of bamboo beams used. If beams are to be stacked together to make a deeper beam they must have regular mechanical fixings, such as bolts, along their length so that they act together. If the poles are simply tied together with wire or rope they will behave individually, and they could just as well be laid flat in a row.

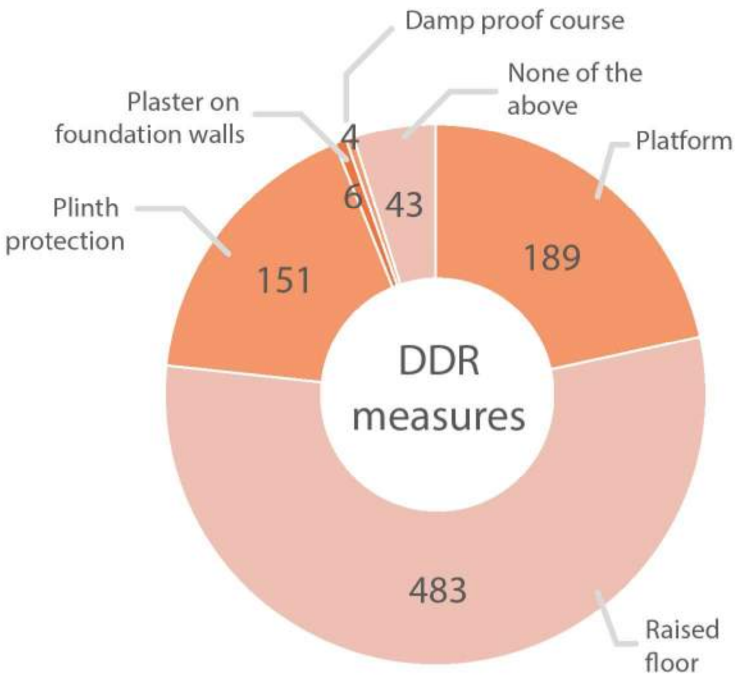
Water resilience

Floor depth vs Elevated floor height



Rain Damage by Roof Pitch





6.3 Water Resilience

Summary

This section summarises the key findings for the water resilience indicator, in particular the relative risk from, and different DRR measures for combating, heavy rain and standing water. With limited resources available to invest in DRR measures it is important that the purpose, effectiveness and cost of these improvements is better understood, enabling informed decisions and clarity on anticipated performance.

Resilience to heavy rain and standing water are discussed in turn in the following sections, with a key finding of this research suggesting that standing water poses a greater risk to shelter and that the approaches to combat the two hazards are different (see table 25). In a flood it is desirable to protect both the structure in order to prevent collapse as well as people and their belongings to enable them to recover faster. Platforms, raised floors, shelves and accessible roofs all enable people to move belongings and or themselves to a level above the standing water. Whilst their purpose may be entirely non-structural, points B.4 to B.6 in table 25 are reliant on the structure remaining standing. For the shelter to remain standing the foundation and wall construction must be of fully waterproof construction to a level above the water.

Raised floors and platforms

Raising the external floor area through construction of a 'platform' provides a dry apron to gather livestock and other perishables, improving community resilience. They were widely implemented with 24% of shelter assessments including this DRR measure. Unfortunately platforms will do little to improve the resilience of

A) Heavy rain	A) Standing water
	Measures to keep shelter standing:
1. Water resilient plasters	1. Foundations to adequate depth in original ground (not fill material)
2. Roof overhang	2. Waterproof materials such as stabilised soil to above level of standing water
3. Drainage	
4. Toes or plinth protection and other sacrificial mass	
5. Stabilisation of mud roof	**Measures to keep belongings dry:**
	3. Platform (external dry area)
	4. Raised floor (internal dry area)
	5. Shelf (limited internal dry area)
	6. Accessible roof

It is recommended that design information and even physical shelters are clearly marked with a line to indicate the maximum standing water level which they might withstand.

Table 25 - The purpose of DRR measures

shelter structures themselves, built up from soil placed by hand they will be quickly eroded by flowing water and will become quickly saturated by standing water, and in the case that the foundations or shelter sub-wall are not waterproof, collapse will occur. The softness of the new raised external ground will also require that the foundations extend down to be founded at least 0.5m into original ground, effectively serving to increase the height of the wall and adding cost.

Raised internal floors, which generate a step from inside the shelter down to the surrounding ground level, were also widely implemented 60% of shelters. Raising the internal floor level serves to protect belongings and occupants provided that the materials from which the shelter is built from are fully water resistant to at least the same height as the raised floor. This was clearly demonstrated with 8 panels failing with standing water below the internal raised floor level.

Notably just 6% of floors had been raised to a level at or above the past flood, and whilst 58% of shelter were subject to a flood of 3ft or more and hence beyond the level to which a raised internal floor could reasonably be built, a further 42% of shelter could have included a raised floor constructed to the previous flood level, but did not. This suggests that shelter agency community consultation did not include gathering data on flood heights or where it did, that the data was not reflected in shelter designs, a suggestion reinforced by just one of the drawing sets including a reference to flood heights.

The height of raised floors and platforms are practically limited by the volume of soil which can reasonably be placed and compacted, limiting the depth of flood that can be combated (~3ft above original ground level). The resilience of the structure may be further improved by using water resistant materials up to the cill level or all the way up to roof level potentially enabling them to withstand standing water.

Alternatively stilted structures could be used and whilst this approach has obvious benefits and is widely adopted in other regions facing similar challenges they are not found in the Sindh, a notable exception being the community centre design developed by Heritage Foundation (http://www.heritagefoundationpak.org/).

Waterproof materials

For a shelter to resist standing water the materials used must be entirely water resistant to a height above the depth of standing water. Where construction switches from waterproof to non-waterproof materials to save cost there should be an impervious layer (damp proof course) to prevent moisture tracking up the wall. It is recommended that design information and even physical shelters are clearly marked with a line to indicate the maximum standing water level which they might withstand.

In practical terms, and unless it is accepted that the shelter will not withstand a flood, this means that the foundations must always be waterproof. If a raised internal floor is employed all materials used up to and ideally above this level should also be waterproof.

This can be achieved through use of fully stabilised (lime or cement) earth construction and fired brick/concrete block with cement mortar, as evidenced by panels 6, 9 and 12 surviving until the end

Concrete Block	5
Fired Brick	5
Adobe	3
Layered mud	3
Loh Kat	3

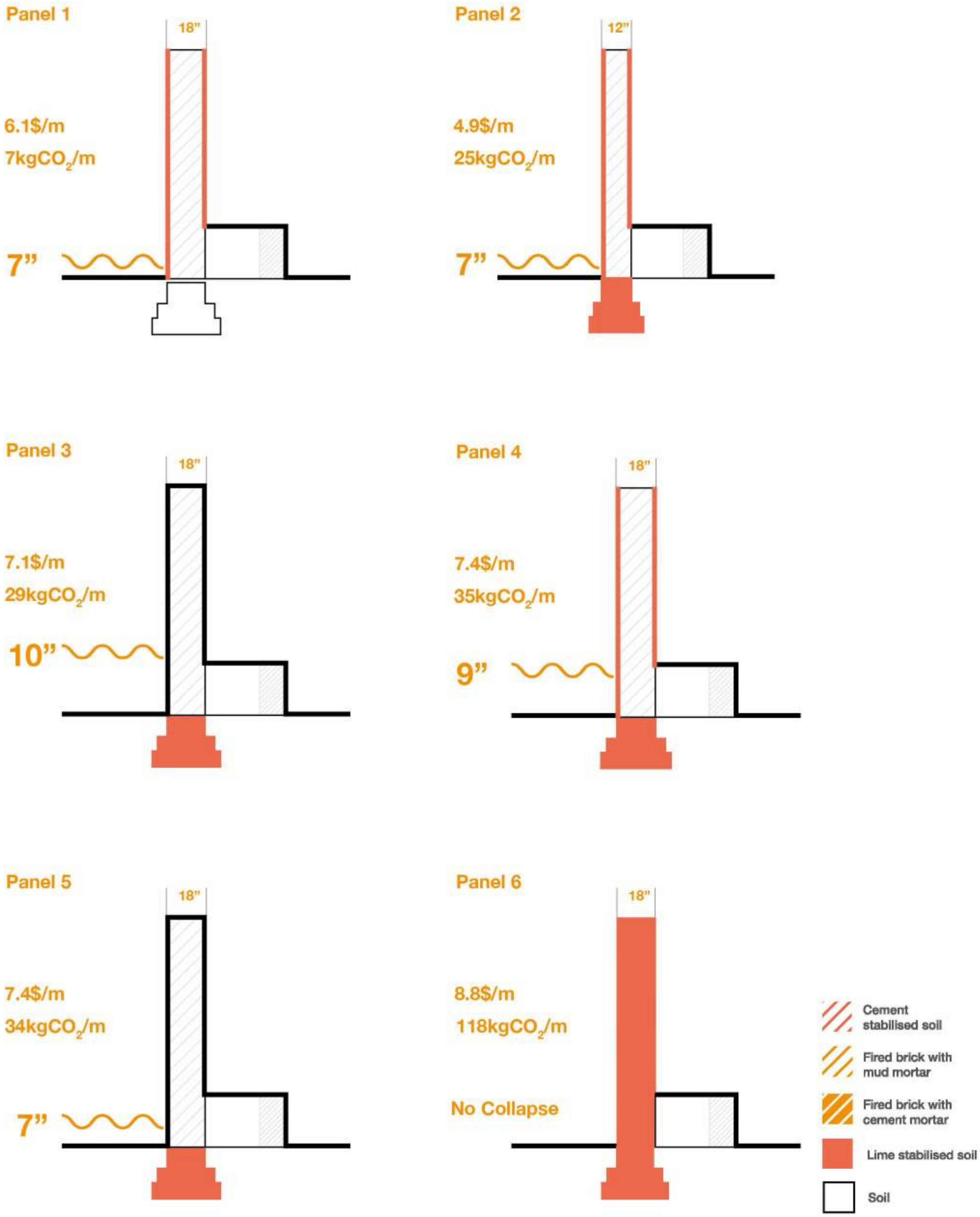
Wall Topology Rank
Waterproof materials

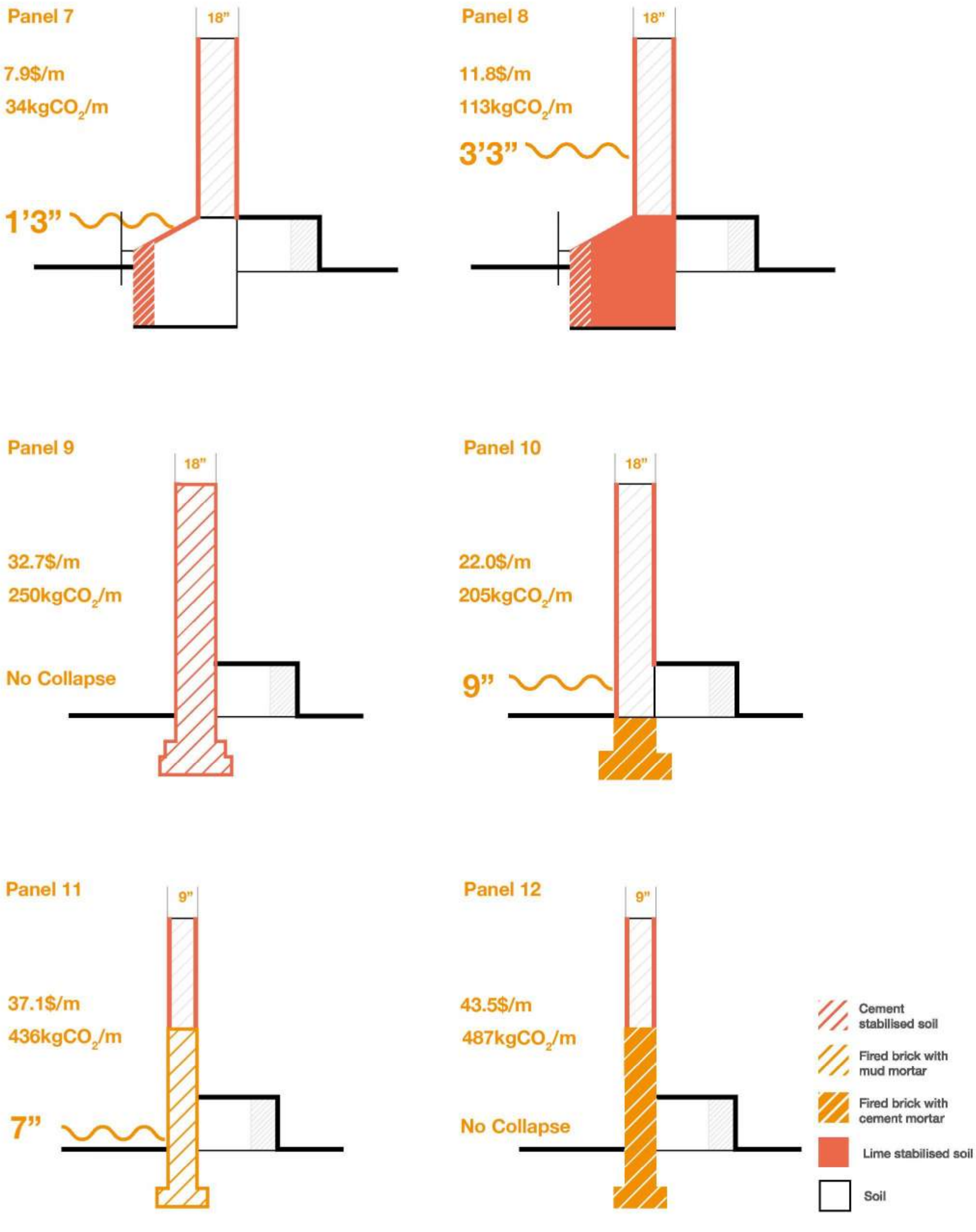
of flood testing. Where stabilised earth is relied upon to be water resistant testing of the finished product, such as by placing an adobe block in a bucket of water to check that it does not dissolve, is essential. A key limitation of layered mud is that it is built in-situ and cannot easily be tested in this way.

Use of lime increased over 2010 – 2012 as a way to improve water resilience of earth construction and was adopted by a number of agencies who introduced training programmes, recognising that its use was unfamiliar and required dedicated specialist knowledge. IOM identified a need for improvement in this area and a dedicated manual (IOM 2015) for using lime in Pakistan was published. At over 150 pages the manual provides detailed technical instructions illustrated with cartoons on how to use lime to stabilised foundations, floors, walls, plasters etc. Refer to section 6.4 for a discussion of the sensitivity of lime to workmanship.

Whilst loh-kat was not included in the flood testing it has the potential to resist standing water, relying upon its timber frame to maintain structural integrity and support the roof whilst the plaster matrix is washed away (See figure 16). Where rapidly constructed loh-kat shelters were performing poorly in terms of structural integrity and stability, this resilience to standing water is likely to be reduced, however this hypothesis is untested by this research (refer to section 9 – Recommendations for further work). In addition loh-kat that is made from softwood or bamboo are liable to rot if left immersed in water for too long.

Figure 16 - Loh-kat shelter after flooding (UN-HABITAT 2010)


Panel 1
18"
6.1$/m
7kgCO2/m
7"
Panel 2
12"
4.9$/m
25kgCO2/m
7"
Panel 3
18"
7.1$/m
29kgCO2/m
10"
Panel 4
18"
7.4$/m
35kgCO2/m
9"
Panel 5
18"
7.4$/m
34kgCO2/m
7"
Panel 6
18"
8.8$/m
118kgCO2/m
No Collapse
Cement stabilised soil
Fired brick with mud mortar
Fired brick with cement mortar
Lime stabilised soil
Soil


Panel 7
18"
7.9$/m
34kgCO2/m
1'3"
Panel 8
18"
11.8$/m
113kgCO2/m
3'3"
Panel 9
18"
32.7$/m
250kgCO2/m
No Collapse
Panel 10
18"
22.0$/m
205kgCO2/m
9"
Panel 11
9"
37.1$/m
436kgCO2/m
7"
Panel 12
9"
43.5$/m
487kgCO2/m
No Collapse
Cement stabilised soil
Fired brick with mud mortar
Fired brick with cement mortar
Lime stabilised soil
Soil

Base protection/sacrificial mass

For the purpose of this study sacrificial mass is defined as any part of the shelter whose primary purpose is to protect the main structure and which does not contribute to its structural integrity. These elements act as a 'wearing' layer which degrades over time and then requires repair whilst protecting the structure behind. Examples deployed in shelter designs included plaster and increased wall thickness whereby wall sizes are increased well beyond that required for strength or stability under normal conditions

Physical testing of these measures has demonstrated that none of the above will improve resilience to standing water, in short half measures do not work. This is evidenced by the following:

- An adobe wall of 18" thick (panel 5) failed just as quickly as an 12" wall (panel 2)
- An adobe wall with a waterproof plaster (panel 5) failed just as quickly as one without (panel 3)

Toes are where additional material is placed in a slope to protect the base of a shelter, with physical testing demonstrating that they should be considered as sacrificial mass to protect primarily against heavy rain and could be though of as the 'boots' in the hat and boots approach (see figure 17). Panels 7 and 8 included toes with varying levels of stabilisation and both collapsed shortly after the water level exceeded the level to which the toe was stabilised. Comparison between panels 6 and 8 shows that distributing the cost of stabilisation up the wall instead of concentrating it at the base gives a structure that is capable of resisting much deeper standing water.

Whilst stabilisation of earth plaster had limited effect in standing water tests it significantly improved performance in heavy rain testing. Adobe walls with lime and cement stabilised plaster lost between 0.1kg and 04kg of their mass compared to a wall where the plaster had not been stabilised, which lost 12.9kg, a huge difference resulting in significant reduction in durability and increased maintenance.

Rain testing also served to indicate that stabilised plaster is still required even where the wall behind in stabilised. Panel 7 (Lime blocks, no plaster) recorded 7.13kg of erosion, again a significant increase compared to the panels with stabilised plaster, indicating that without plaster a wall would require more frequent repair, an issue which would be compounded by the difficulty of repairing the blocks themselves.

Rain testing supplemented with structural analysis has also shown that heavy rain alone should not be the cause of shelter collapse. Subjected to the heaviest ever rainfall recorded in the Sindh an unstabilised adobe wall with no plaster remained standing, losing 10.8kg or less than 1% of its overall mass. It follows that a shelter wall would have to be in very poor condition and lacking basic detailing such as overhangs and lintels for failure to occur.

Drainage and overhangs

Drainage should be provided both at roof and the base of the building in order to carry rain water away and prevent standing water. Roof overhangs provide protection to the upper walls preventing. This is especially important for materials which have low water resistance such as earth construction and forms part of the 'hat and boots' approach to ensuring durability of vernacular construction.

Shelter assessments recorded an average overhang of 0.35m significantly less than the recommended 0.8m (Walker, P 2002), with very little variation between the typologies, indicating that the need to increase overhangs to protect earthen construction is not well understood. Roof overhangs also provide external shade, creating additional usable space when it is hot.

Heavy rain is also known to saturate mud roofs, increasing their weight, a scenario which was investigated in the structural analysis, refer to section 6.2 –connections and tieing. Where this failure did occur it is likely that the lack of a roof overhang could have contributed to saturation and loss of strength of the upper wall.

Surprisingly roof slope was found to be independent of damage, with similar levels of minor and major damage found for flat and sloped roofs. Roof drainage measures were sparsely applied with 29 water spouts and 22 drainage pipes recorded.

Where base drainage is included this should be co-ordinated with access routes and other nearby channels, taking care not to displace the issue by causing localised flooding elsewhere. These issues should be considered as part of a site selection, appraisal and planning process and are outside the scope of this study.

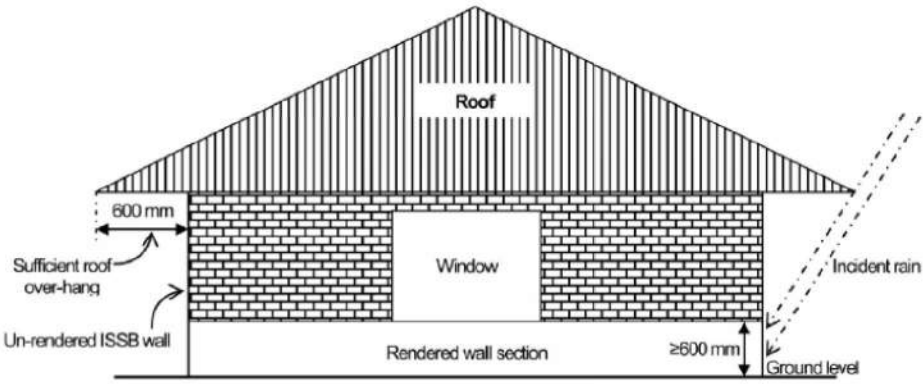
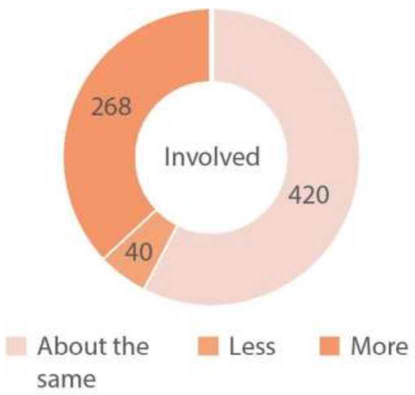


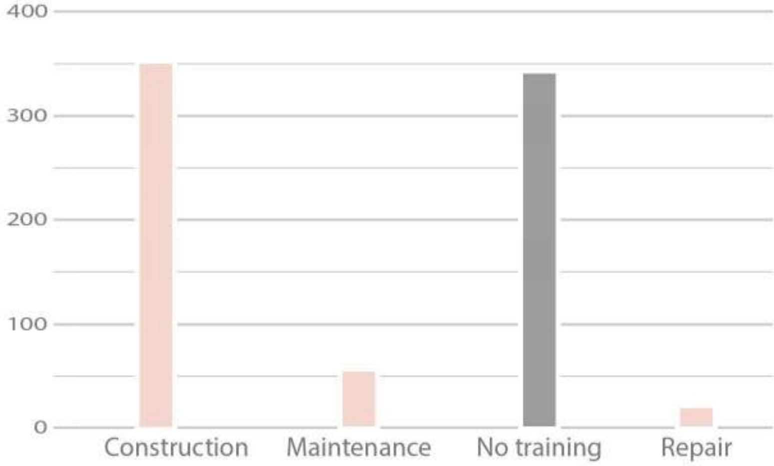
Figure 17 - Hat and boots approach to protecting earth construction (Andabati, D 2010)

Buildability, maintenance and modification

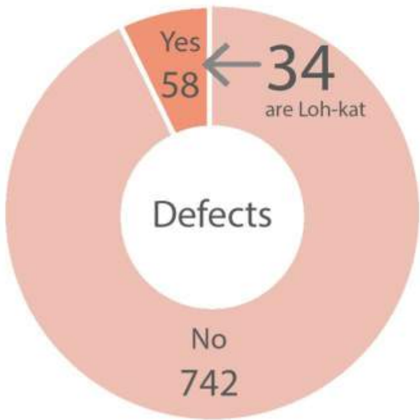
Would you like to have been more or less involved in construction?



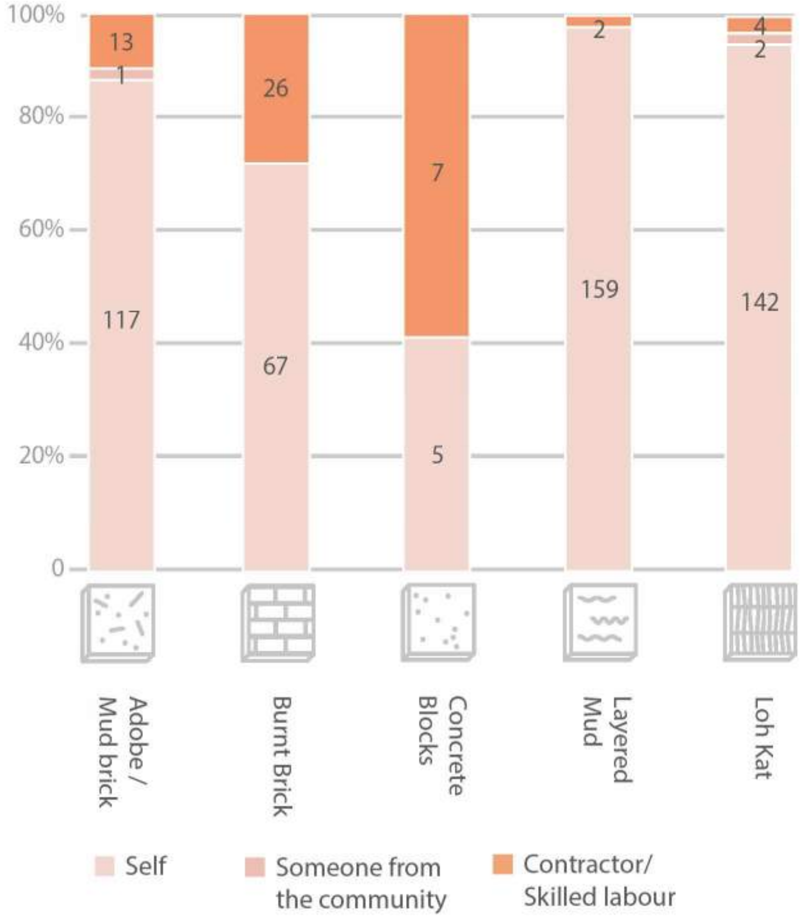
Type of training given



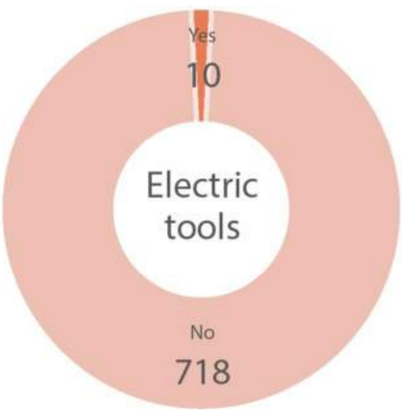
Are there gaps in the walls due to construction defects?



When repairs are needed, who carries them out?



Were electric tools used?



74%

repaired or modified with locally available tools

6.4 Buildability, maintenance and modification

Communication

The quality of a building is defined by design, materials and workmanship. The first step in achieving a given standard of construction is quality assured design information which is complete and clear. Design information should include fully annotated and dimensioned plans, sections and elevations and connection details. Materials used should be fully specified with sizes, properties and treatments required.

The design information review confirmed that this is an area where improvements can be made with 90% missing information required to constitute a complete design, this included dimensions and location of doors and windows[1], spacing for roof purlins or joists, and connections between members. This confirmed the need for design guidance which the shelter guide aims to address.

Buildability

For a design to be realised as per the intent it must be buildable (https://www.designingbuildings.co.uk/wiki/Buildability_in_construction), with familiarity with construction techniques and complexity of detailing, for example around connections, being key. Where specialist training is required it is indicative of unfamiliar or possibly complex techniques, such as use of lime. Buildability can be crudely quantified by length of construction programme. Whilst construction defects may be indicative of poor buildability they may also be the result of design and materials quality. Where a design or parts of the design have been replicated at a local level this is indicative of a buildable design that has been well communicated.

Tools and skills availability are particularly closely linked but have been kept separate to provide additional definition around this critical area.

Data from key informant interviews is summarised below illustrating that roof, floor and foundation construction duration are similar across the typologies, with the exception of loh-kat, which is notably faster. Nominally whilst a loh-kat shelter could have the same floor or roof as an adobe shelter the data suggests that less effort is dedicated to the same component when it comes as part of a loh-kat design. Adobe walls take reportedly longer to construct compared to the other masonry types and construction is further slowed by the need to manufacture the blocks, which are formed by hand in moulds. Where lime is added the blocks should be cured for a period of 30days before use. This is backed up in the field by anecdotal reports from surveyors that homeowners preferred layered mud over adobe as it can be constructed rapidly in-situ with limited or no lead in time.

Whilst the rapid assembly of loh-kat may be viewed as an advantage this conversely may be a contributory factor in the finding that 59% of all shelters with construction defects were loh-kat.

Just 56 (7%) homeowners reported that a neighbour had copied part of their shelter, with raised platforms and raised floors most likely to be replicated, with cost quoted as the key barrier.

1 *Openings act as weaknesses and if they are too large or too close together they can impact the structural integrity of a wall, see section 6.2*

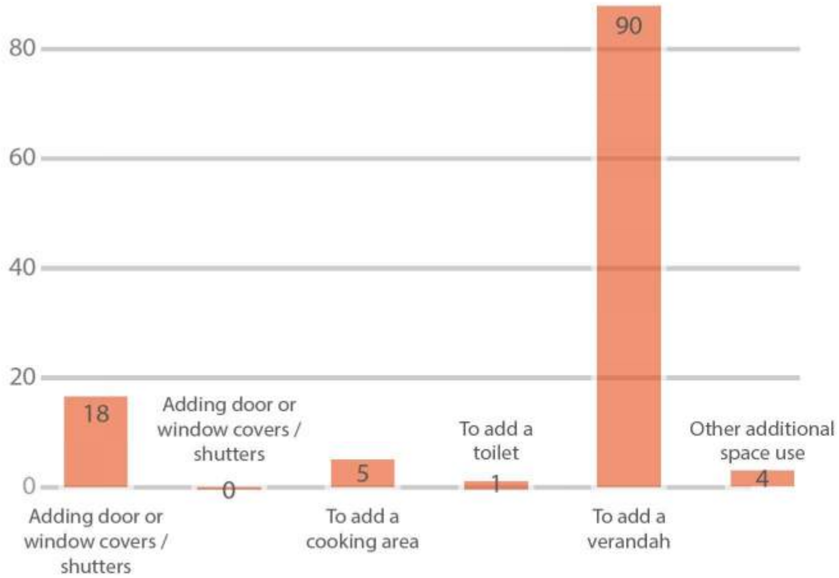
Loh Kat	5
Fired Brick	4
Layered mud	3
Adobe	1
Concrete Block	*

Wall Topology Rank
Buildability

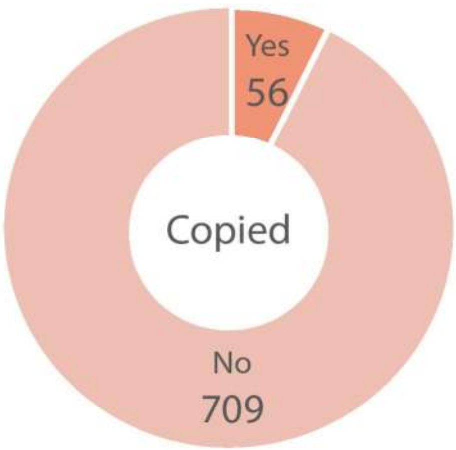
*No data

Buildability, maintenance and modification

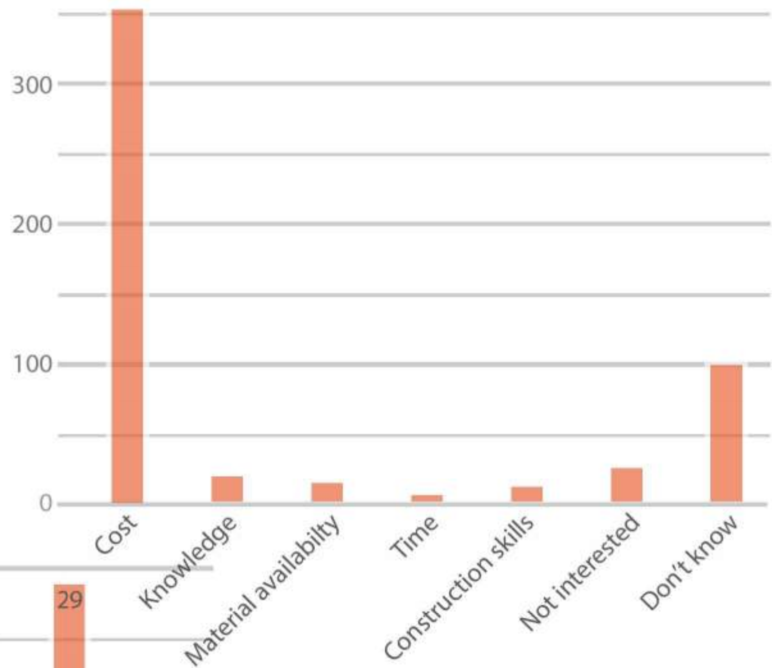
Modifications to Shelter



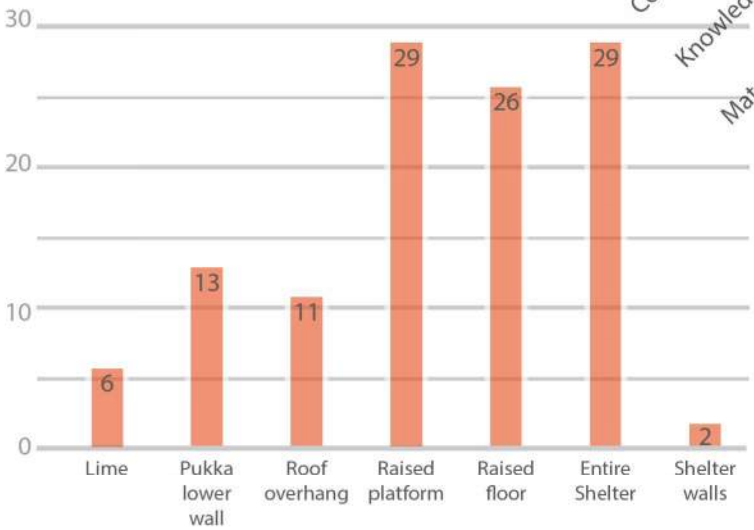
Do you know of anyone who has copied this Shelter design or parts of this Shelter design?



What prevented people from copying the Shelter



What part was copied?



Correct use of lime requires an understanding of the soil and lime through testing such that suitable mixes are designed. Following a one month curing period trial mixes are tested to understand their strength and water resistance. This process requires both time and training. This added complexity and the barriers it poses to local uptake were recognised by Heritage Foundation who proposed a simplified approach and a standard mix for different shelter components. This approach will certainly improve buildability but also serves to reduce performance of the lime stabilisation in locations where local soil does not suit the standardised mix.

The sensitivity of lime to workmanship was demonstrated during physical testing when the foundations for five of the flood panels did not set correctly as a result of insufficient kneading (mixing). It is unlikely that the defect would have been caught or corrected if constructed in the field and the occurrence of the defect under the supervision of an IOM shelter expert in the controlled environment of a university experiment is indicative of sensitivity of lime to workmanship. Once the defect had been identified the foundations had to be rebuilt incurring additional cost and time. Where lime is used it must be the subject of focussed training.

Whilst Portland cements is significantly more expensive it requires a single test to judge soil suitability and less preparation overall compared to lime stabilisation.

Tools

In order to build, maintain and modify their shelter homeowners need access to the tools required. Shelters performed well in this respect with 74% of homeowners responding that they did, whilst just 1% reported that power tools were used during construction, highlighting the dearth of resources available. Key informants reported providing a chisel, hammer, level, saw and sometimes a wheelbarrow as part of a toolkit.

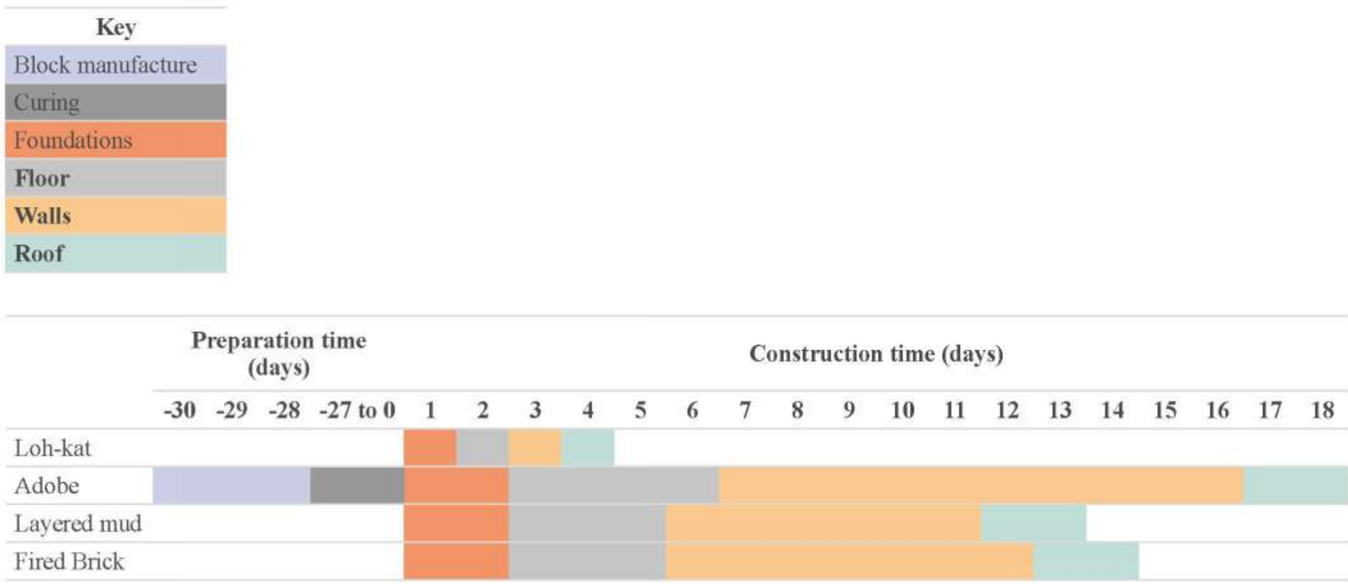
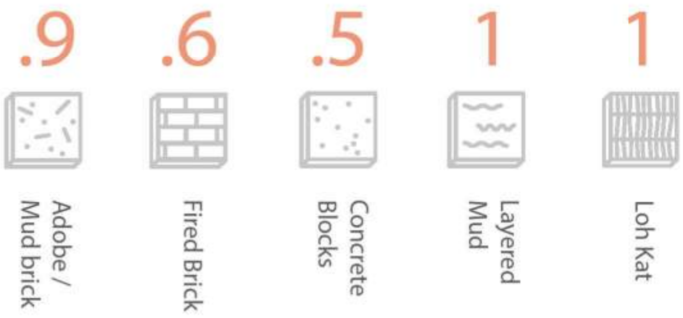


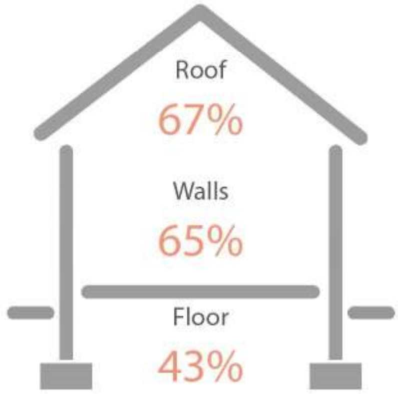
Figure 18 - Construction programme summary

Maintenance and Repair

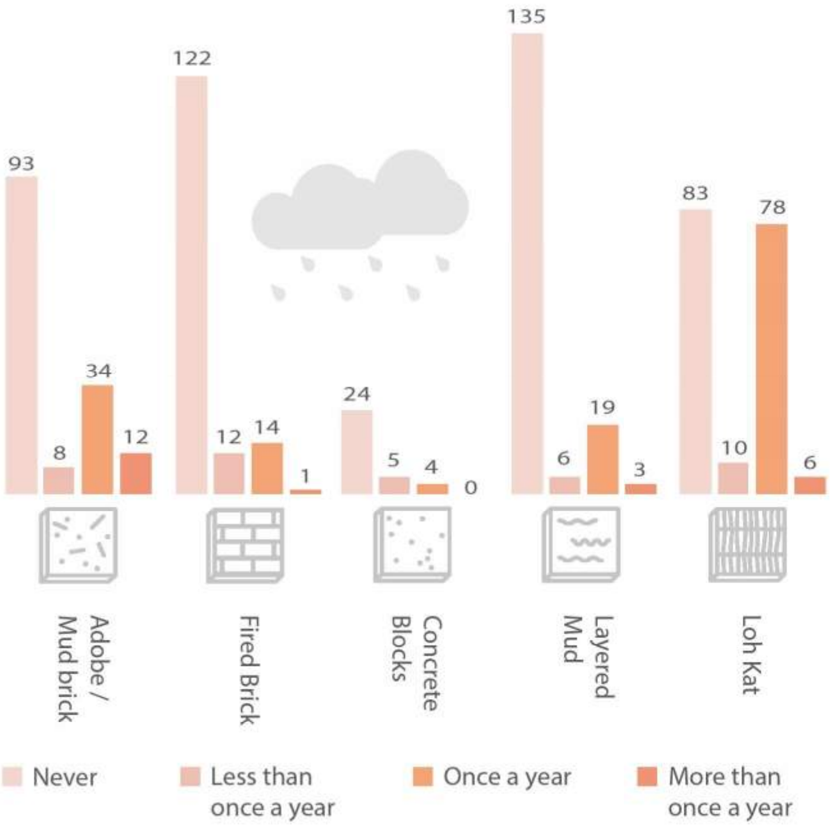
Average number of repairs per year



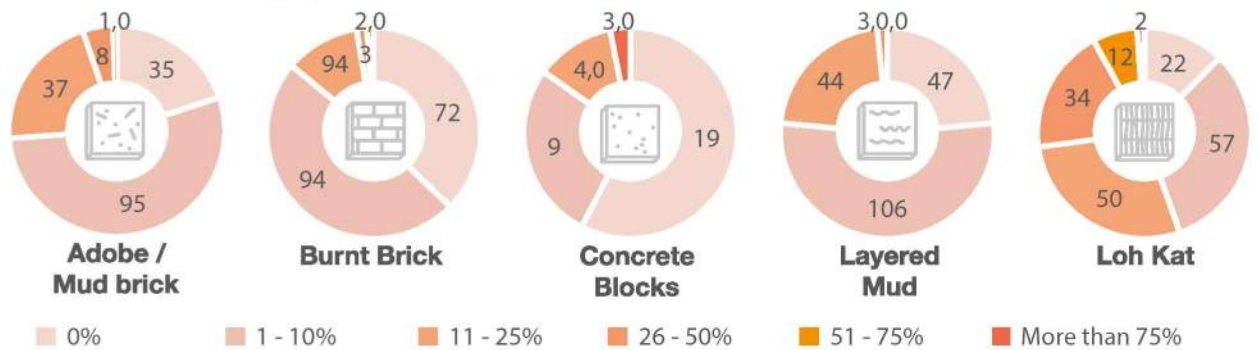
What needs repair?



How frequently does rain damage your shelter?



What proportion of the wall is damaged or deteriorated?



Skills availability

It is useful to divide construction skills into unskilled and skilled, the later covering trades such as carpentry and masonry. Unskilled labour is typically cheaper and more widely available, with basic training enabling homeowners and communities to fulfil these roles. Typologies that maximise use of unskilled labour will be inherently more buildable.

Key informant interviews suggested that during construction there was relatively little difference in the number of workers or division between unskilled/skilled across wall typologies with an average team of four, consisting of one, sometimes two skilled labourers and two or three unskilled labourers.

However, when it came to maintenance homeowners with fired brick shelters were more likely to have hired a skilled labourer, with fired brick shelters more expensive to maintain as a result.

Training

There is wide consensus on the need to provide training to build capacity of local communities in order to facilitate self-recovery, with all agencies interviewed providing training of some sort, an assertion confirmed by the homeowner surveys with 57% provided with construction training. This training was generally well received with 95% stating it was sufficient. Homeowners are more inclined to want to be more involved rather than less involved in the future. By way of improvement, future training programmes could look to address maintenance and modification, for which just 7% and 3% of homeowners received respectively. Shelter Centre's evaluation (Shelter Centre 2014) suggested that training would benefit from being more practical in nature but also reported that the process of homeowner involvement in construction served to reinforce women's traditional role as builders, increasing their workload overall.

Maintenance and repair

With limited resources in terms of materials and skills minimising the frequency of maintenance is a key design driver. Roofs and walls, which are both exposed to weathering, are most likely to require maintenance with homeowners reporting that 67% and 65% needed repair respectively, whilst 43% needed to repair the floor, which is subject to wear from foot traffic.

Fired brick and concrete block required repair on average once every two years, with loh-kat, adobe and layered mud all requiring repair once a year. Whilst frequency of repair for loh-kat, adobe and layered mud were reportedly the same, loh-kat walls were observed to be significantly more 'damaged or deteriorated'. Rain or 'unknown' were the main causes of damage whilst construction defects were reported in 9%, over half of which were observed in loh-kat shelters. Stakeholder consultations reported that flexibility of 'chicks' reed matting used for some loh-kat walls was causing plaster to deteriorate over time

Loh Kat	5
Layered mud	3
Adobe	3
Fired Brick	1
Concrete Block	1

Wall Topology Rank
Skills Availability

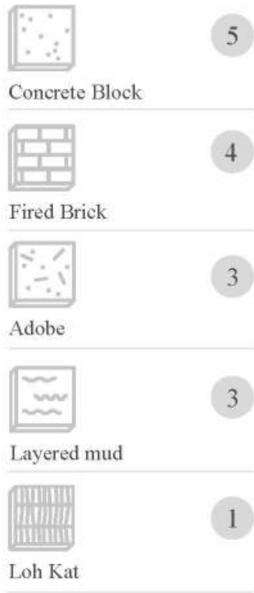
Concrete Block	5
Layered mud	5
Adobe	5
Fired Brick	2
Loh Kat	1

Wall Topology Rank
Training

Modifications

One quarter of all respondents reported having modified their shelter, with the most popular modification. Verandas provide the obvious benefit of external shaded space and also serve to improve thermal performance by providing shade to the shelter itself. Conversely they are known to be at risk of being torn away during high winds causing damage to the main structure in the process. This risk could be mitigated through consideration of veranda addition at design stage and subsequently during provision of training.

Other modification included adding window and door covers/shutters whilst expansion of living space through additional rooms barely factored (<1%), again pointing to the limited means of the survey population.



Wall Topology Rank
Maintenance and repair

7
Acceptable to occupant

7.1 Comfort

Thermal and ventilation

Thermal comfort and ventilation performance can be measured by comparing internal air temperature and occupant temperature to external air temperature in the shade. Without the aid of mechanical cooling internal air temperature may at best match the external air temperature in the shade. Where thermal mass is employed the resulting cooler surface temperatures may serve to reduce the occupant temperature below the external air temperature in the shade.

Homeowner opinions on temperature are inherently subjective, with few trends discerned from the data. 10% of homeowners reported having insufficient ventilation as a reason for not using the space as they wanted. Shelter assessments highlighted that very few shelters had openings in more than one wall, negating the impact of cross ventilation. Stakeholder consultations recorded that where the branches and sticks to be used in reed wall construction are of good quality, some communities may choose not to apply plaster, increasing ventilation.

Further analysis of the shelter assessment data could find no correlation between internal temperature and wall material, thickness or window opening area. Interrogation of the thermal analysis model confirmed that this is due to the predominant effect of the door opening on ventilation and thermal comfort, due to its relatively large size when compared to shelter floor area.

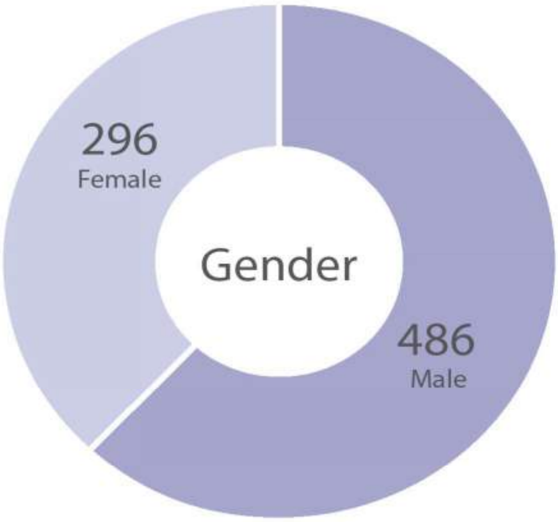
Of the design improvements explored in the model (see table 26), increased roof thickness had the greatest reduction in operative temperature, followed by optimised location and size of ventilation openings.

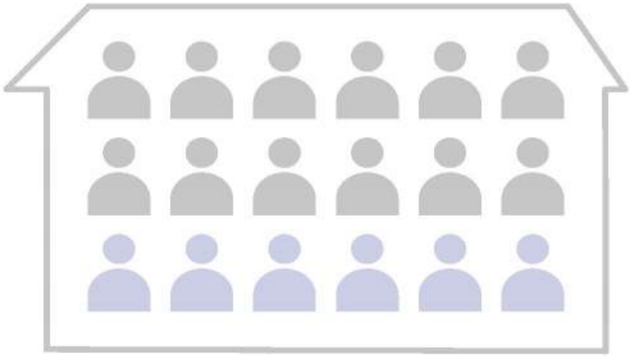
Wall Topology Rank
Therrmal

Model	a		b		c	
	Air Temp	Operative Temp	Air Temp	Operative Temp	Air Temp	Operative Temp
Openings						
a) average ventilation openings b) 2.5% floor area low level and high level	-0.66	-0.87	-1.19	-1.74	-0.53	-0.87
Orientation						
a) Front of shelter orientated West vs b) North	-1.04	N/A	-1.43	N/A	-0.39	N/A
Wall thickness						
a) Average wall thickness (12”) vs b) increased wall thickness (18”)	-0.66	-0.87	-0.90	-1.54	-0.24	-0.67
Roof thickness						
a) Average roof thickness vs b) increased roof thickness	-0.66	-0.87	-1.17	-2.09	-0.51	-1.22

Table 26 - Thermal comfort analysis results where a) represents average existing shelter b) represents a design improvement

Demographics





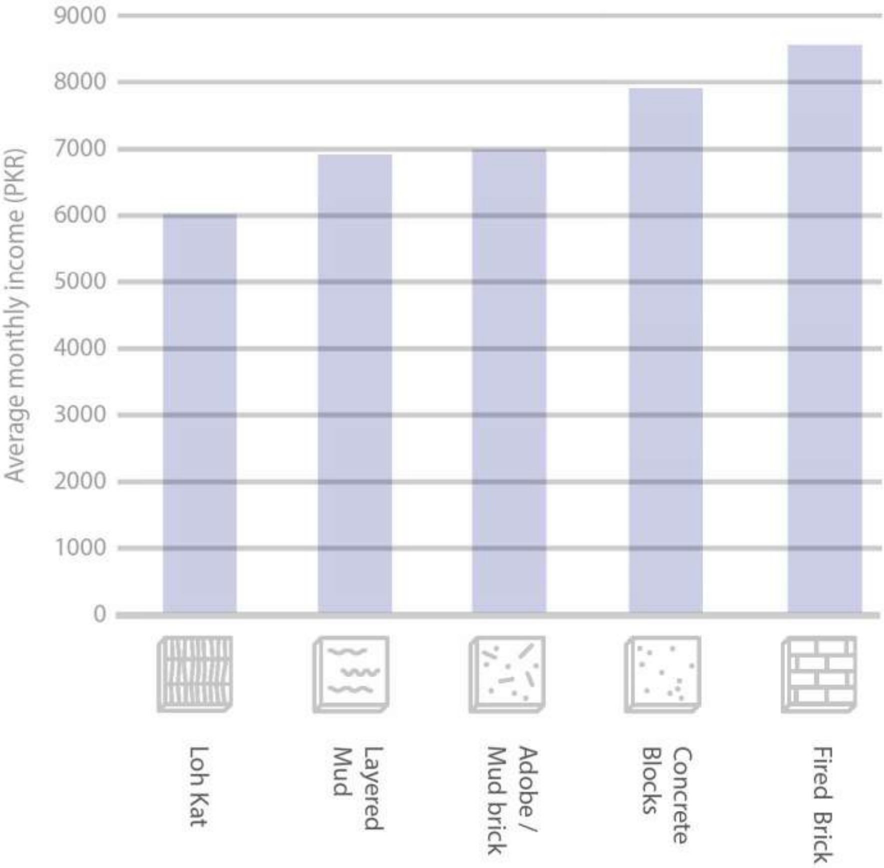
6 people on average per shelter, up to 18

Family Member	Average Age
Husband	41
Wife	34
Son	10
Daughter	9

2/3 of beneficiary respondents were farm labourers

1/4 were unskilled construction labourers

Shelter wall material against average monthly income



7102 PKR

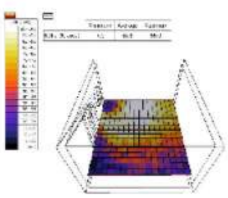
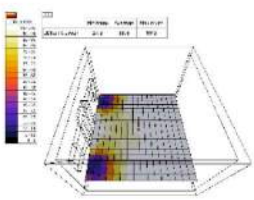
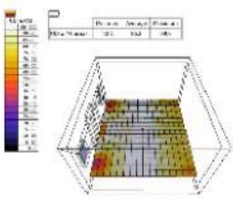
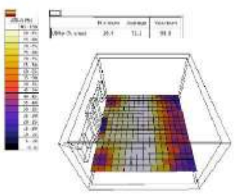
(USD 67) Mean monthly income

Lighting

Whilst shelter were reported as too dark for the local partner to take good photos insufficient daylighting (2%) and insufficient electric lighting (4%) were both low priority concerns for homeowners. Photos suggest that homeowners are choosing to permanently block window openings, serving to reduce the light coming into their shelter (see figure 19), a decision presumably driven by privacy and security concerns, but indicative of lesser priority placed on natural light, an attitude common to hot countries where direct sun light quickly leads to overheating.

The daylight model desk analysis demonstrated the following:

- Two windows 0.6x0.9m would provide adequate daylight for nearly 90% of the time.
- A single window 0.6x0.9m would provide adequate daylight for nearly 70% of the time. Refer to the methodology for an explanation of how 'adequate' was defined.
- Where there is a desire to limit openings, painting walls a light colour can improve daylight performance by up to 30%.
- Jali brick screens (see figure 20) with a 50% open and 50% closed pattern reduce daylight performance by just 5% while providing inherent security and privacy.

No.	Windows	Wall reflectance	Average Useful Daylight Illuminance*	Diagram
1	1no. 0.6x0.9m	Painted white	65.8	
2	2no. 0.6x0.9m	Painted white	88.6	
3	2no. 0.6x0.9m Jali screen (50% closed)	Painted white	86.2	
4	2no. 0.6x0.9m	Observed values	72.1	

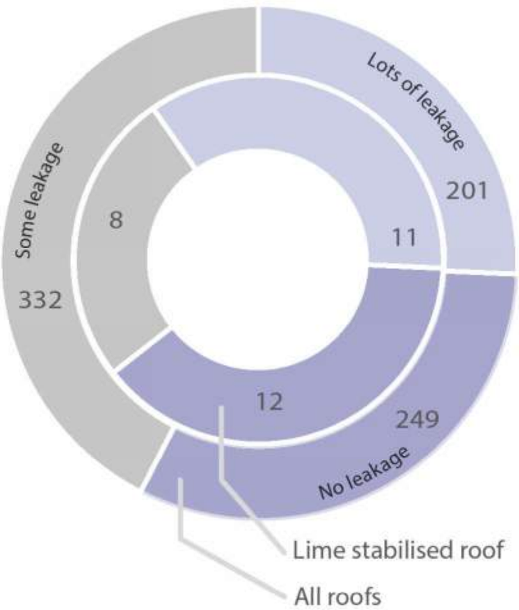
*Note: Percentage of the shelter area that is within 100 to 2000 lux between 9am and 5pm over the course of a year

Table 27 - Daylight model summary

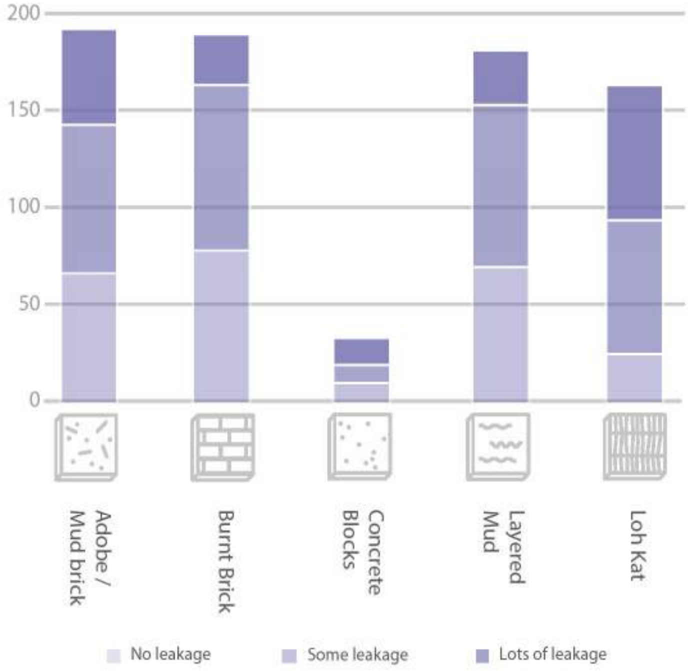
Comfort

Waterproofing

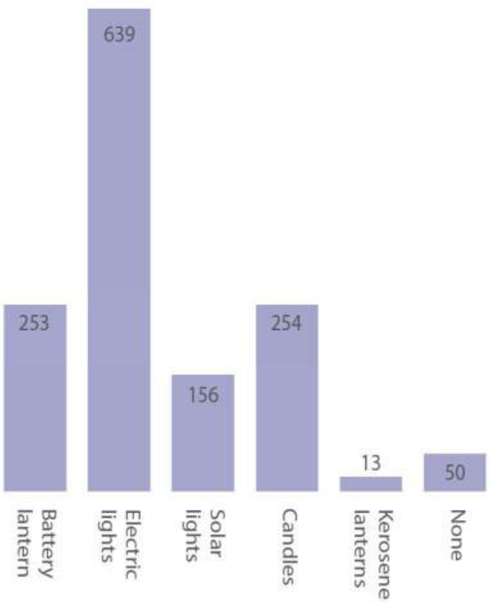
During rainfall does your roof leak?



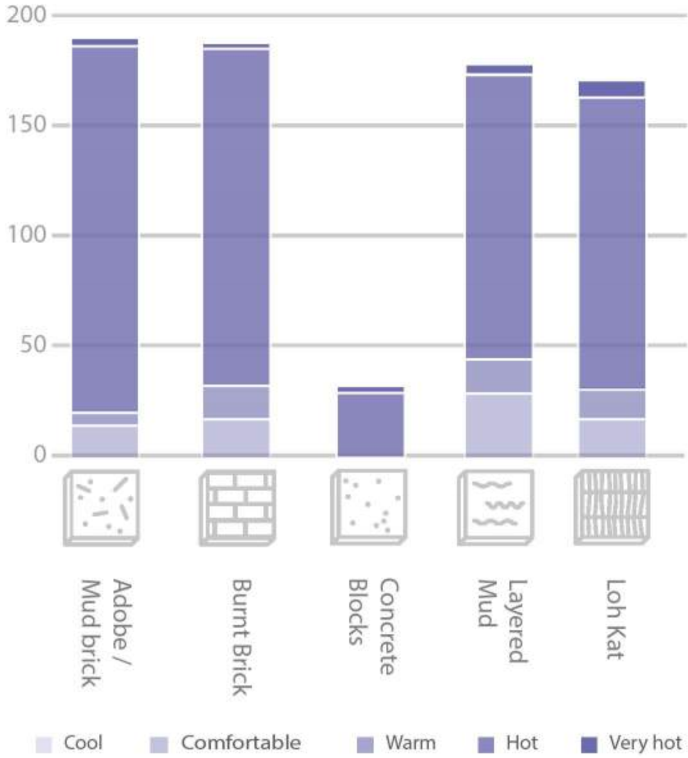
Leakage



Lighting



Thermal comfort on a summer day



4% reported insufficient electric light

2% of homeowners reported insufficient daylight to use the shelter as they wished

9% of homeowners reported insufficient ventilation to use the shelter as they wished

Figure 19 - Modifications made to windows by homeowners seeking to address concerns over privacy and

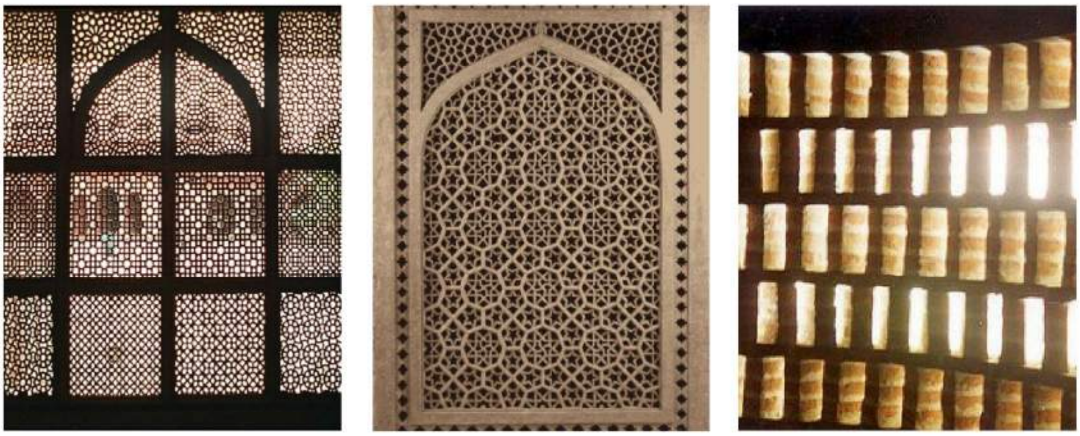
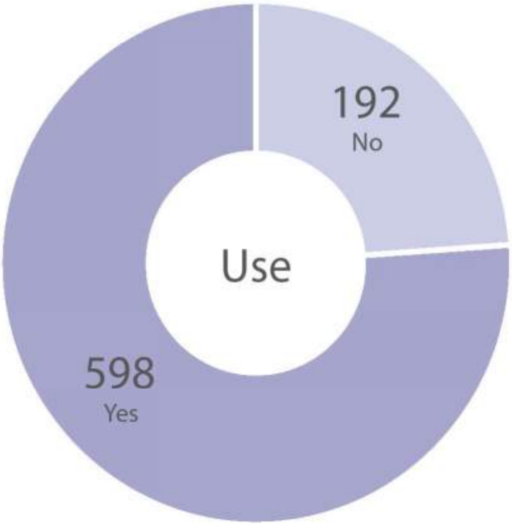


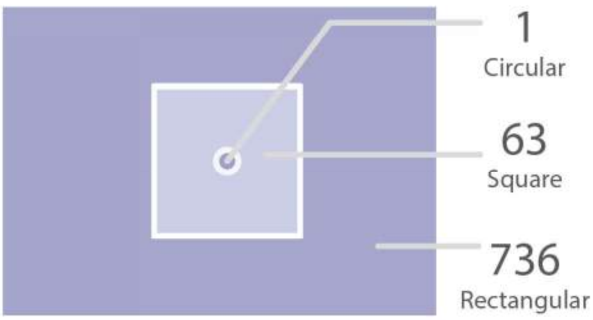
Figure 20 - Jali screens are an ancient technique for providing airflow and natural light whilst maintaining security and privacy by utilising contrasting light conditions to obstruct the view inside. Whilst theses ornate versions are unlikely to be appropriate brick screens are locally achievable (Photo sources: http://blankinship-web.com/sabbatical01/India/Agra/fs-stone-screen.jpg, http://asiangrc.com/grc-screens/ and https://www.new-learn.info/packages/clear/visual/buildings/elements/wall_roof/jali_wall.html)

Space

Are people able to use the shelter as they would like?



Layout

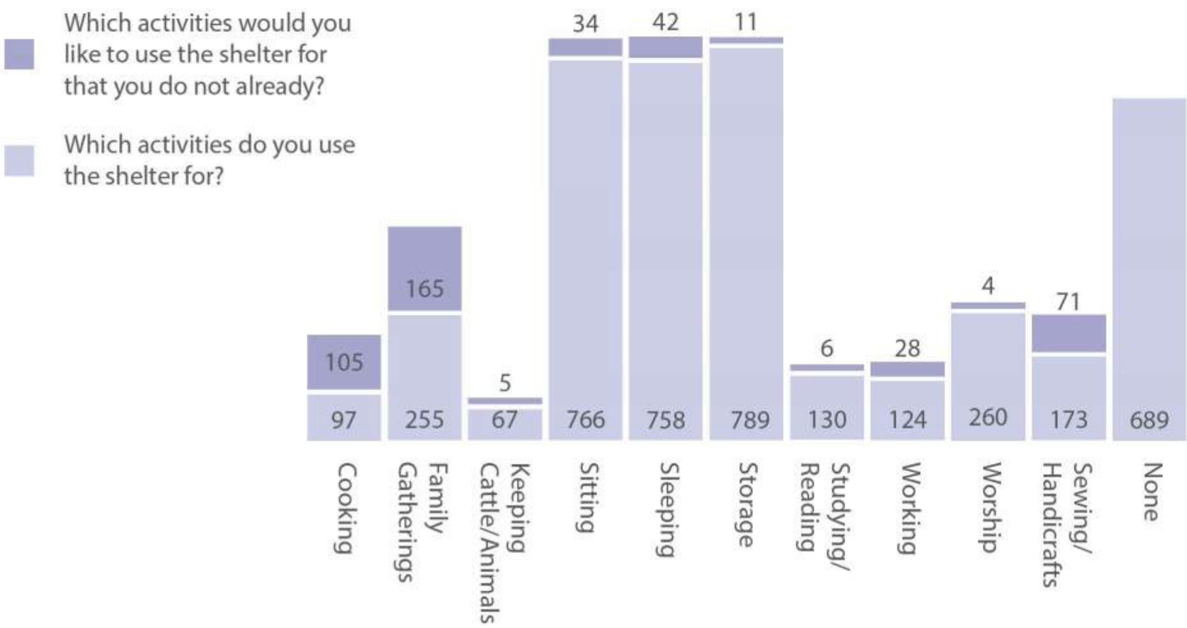


$3.5m^2$ Sphere Standard

$3m^2$ average across all surveys

48% of shelters complied with the standards

Use of Shelter



Weatherproofing

Waterproofing is fundamental to protecting homeowners from the climate as set out at the start of the Sphere Standards (Sphere Project 2004). With nearly three quarters of homeowners reporting that their roof leaked some or a lot of the time this was a notable weakness in the designs. Of the 31 mud roofs that had been stabilised with lime there was no notable improvement over those that had not. Although the small sample size precludes drawing firm conclusions this would again suggest lime stabilisation did not achieve its potential. Typically flat roof are thought to be more prone to leakage but in this case no discernable pattern could be determined between the angle of roof slope and reported leakage.

Loh-kat shelters were more likely to have lots of leakage and less likely to have no leakage compared to the other typologies. The same roof covering material constructed on loh-kat shelter performs worse than the same roof covering built on any other wall typology.

7.2 Space

Size

Minimum standards for space are set out by Sphere for temporary or non-permanent shelter, and their applicability here is debateable. On average six occupants were living in each shelter with a maximum of 16. With an average area of 17m2, this equates to just under 3m2/person, slightly below the Sphere standard minimum of 3.5m2. In total just under half (of shelters meet or exceed the sphere standards. 20% of people stated they could not use the shelter as they like due to lack of space.

Of the different wall typologies loh-kat tended to be largest, this could reflect the cost effective nature of lo-kat allowing larger shelters to be built.

Layout and flexibility

The majority of shelters (92%) were rectangular on plan whilst just one was circular and we note that Heritage foundation discontinued their circular plan shelters.

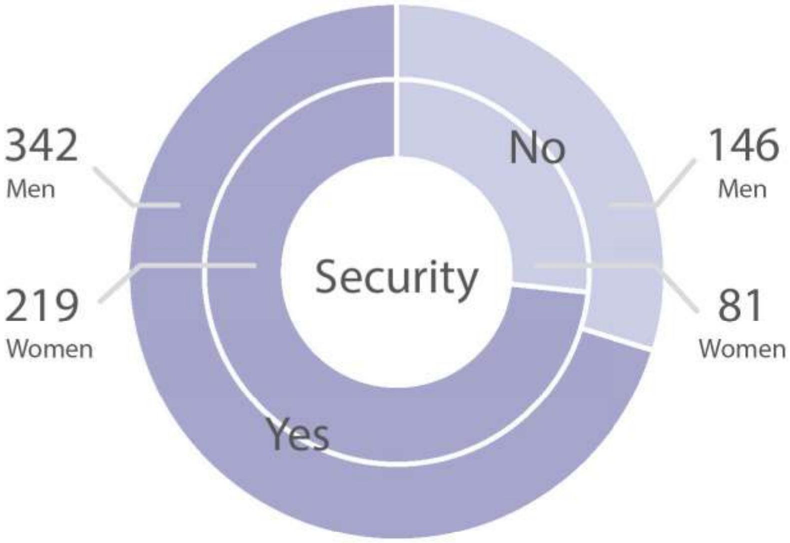
The primary functions attributed to the shelters are sitting, sleeping and storage. In a few cases, they are also used for worship, family gatherings and sewing/ handicrafts. Moreover, the vast majority (86%) of respondents did not identify any other activities for which they would like to use their shelters. The absence of internal partitions were not mentioned as affecting how homeowners use the space.

Loh Kat	5
Concrete Block	4
Adobe	3
Fired Brick	3
Layered mud	1

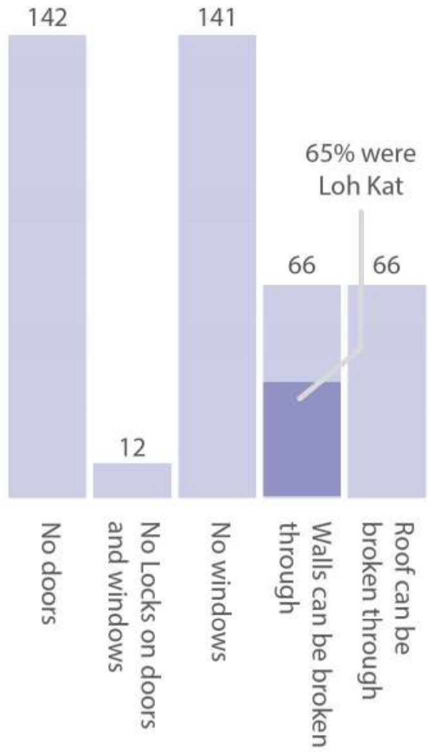
Wall Typlogy Rank
Size

Protection

Do people feel safe - Male vs Female



Reasons why people do not feel safe



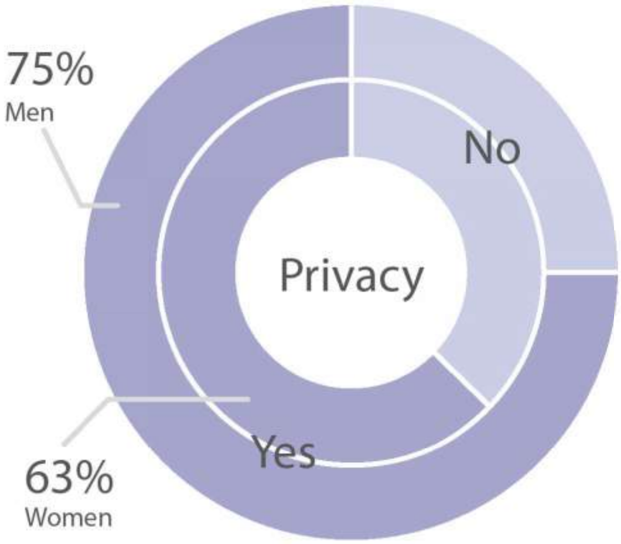
71% said they feel safe in their shelter

70% of people feel their shelter is private

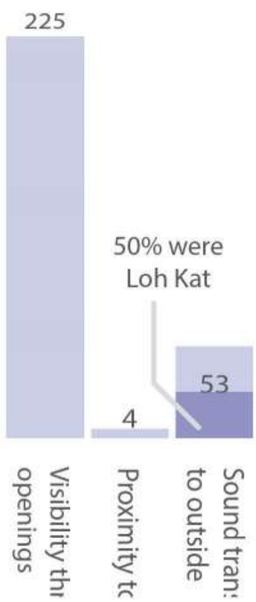
34% of all shelters had no door

1/2 of the homeowners did not report this as a security issue

Do people have sufficient privacy - Male vs Female



Reasons why people do not have sufficient privacy



Percentage of shelter occupiers with sufficient privacy by wall typology

Loh Kat	54%
Fired Brick	89%
Adobe	63%
Layered Mud	69%
Concrete Block	70%

7.3 Protection

Protection was measured through perceptions of personal security and privacy. The results were heavily influenced by common practice amongst agencies of constructing shelters without window or door coverings, on the assumption that they would be fitted later by the homeowner. At the time of survey 34% still had no door covering and a further 3% had no lock or bolt to secure the door. 1% had no window covering and a further 3% had no means to lock the window covering.

Security

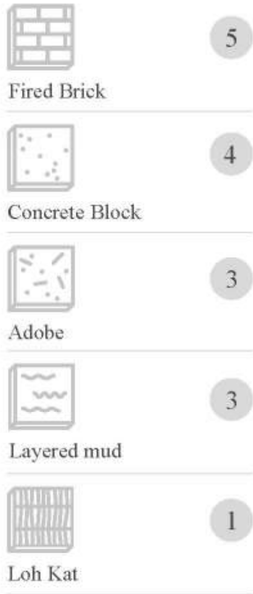
Overall, survey respondents felt secure (71%) in their shelters, with relatively little difference between men (70%) and women (73%). For the significant minority that didn't the absence of windows or doors (18%) were the primary cause. For 8% of homeowners the fragility of walls and roofs were also of concern, with the majority of them 65% living in loh-kat shelter, whose walls are typically thinner and less sturdy than the other typologies.

The homeowner surveys did not distinguish between personal security and belongings, which could be worth exploring in the future.

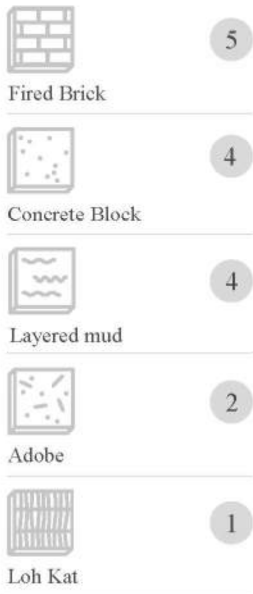
Privacy

A similar minority felt they had insufficient privacy, although this concern was not equally shared by men (25%) and women (38%). Visibility through openings being the primary reason, followed by sound transmission to outside. Where sound transmission was identified as an issue over half of all cases were Loh-kat. Where visibility was an issue this occurred much more evenly between the material typologies, as openings are independent of material typology.

Visibility, if not security through openings should be straightforward to address with material strung above to act as curtains.



Wall Topology Rank
Security



Wall Topology Rank
Privacy

Health and safety

15% cook on an open fire in their shelter

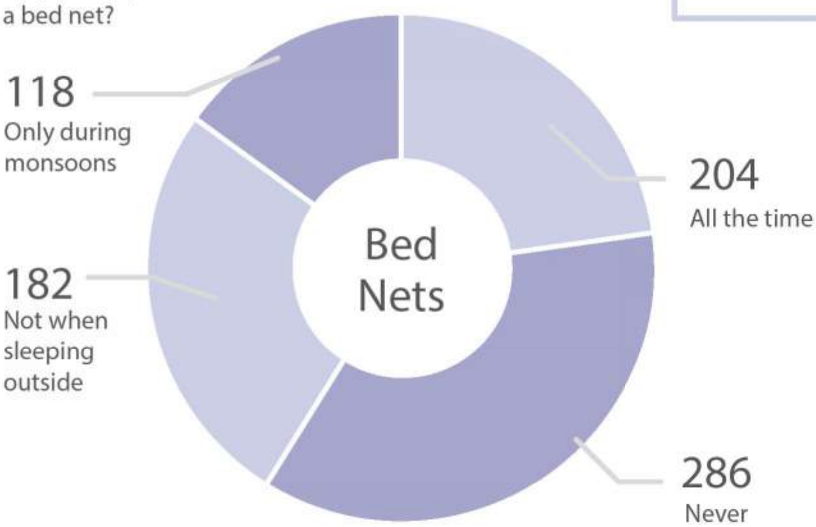
A further **13%** would like to cook in their shelter but currently do not

5m average spacing between shelters

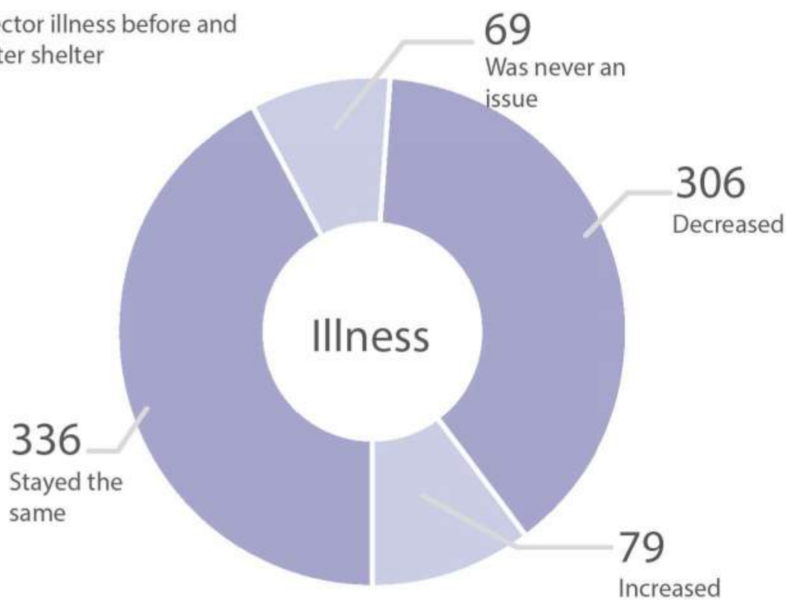
Percentage of shelter occupiers who have had an open fire inside their shelter

Loh Kat	22%
Fired Brick	5%
Adobe	13%
Layered Mud	12%
Concrete Block	9%

Do you sleep under a bed net?



Vector illness before and after shelter



7.4 Health and Safety

Internal Air Quality

Internal air quality is determined by the level of pollutants in a room offset by the level of ventilation provided, as movement of air through the shelter serves to dilute pollutants. For homeowners the primary source of air pollution are open fires used for cooking, fortunately just 12% reported doing so, with another 13% reporting that they would like to cook in their shelter but currently cannot. A disproportionate number of which were in Loh-kat shelters, which if read alongside variations in average income could be linked to economic status. Of those who reported cooking inside 65% reported discomfort due to the smoke.

Air flow analysis found that natural ventilation through openings would be insufficient to maintain air quality at acceptable levels (ASHRAE 62.1 2010) without making the openings unacceptably large. For acceptable air quality to be achieved open fires should be outside of the shelter. In theory dedicated flues could help but in practice are unlikely to achieve the desired results. It should be noted that just under half of those who cooked on open fires in their shelters did have flues, however this did not serve to reduce discomfort from smoke. Smokeless stoves are another option, if available. Finally, it was noted that none of the drawings reviewed considered cooking.

Fire Hazards

Fire risk can be assessed by determining sources of ignition, combustibility of materials, potential for fire to spread and means of escape.

The key source of ignition is cooking on an open fire and is another reason why this should be discouraged. Analysis of the typologies suggests that loh-kat presents the highest risk, particularly in the case the earth render has degraded and the wooden framework is exposed. With shelters located on average more than 5m from each other the risk of spread of fire to neighbours is low and given that the shelters are a small single room, the benefit of two means of escape is limited.

Concrete Block	5
Layered mud	5
Adobe	5
Fired Brick	5
Loh Kat	1

Wall Topology Rank
Fire hazards

Vector Control

Methods to reduce mosquito borne illness include meshing over openings and bed nets. Inclusion of netting over opening or other vector control measures were not included on any of the drawings reviewed. Installation of mesh over door openings and gaps between walls and roofs is fiddly, availability of mesh is unknown and durability is an issue.

26% of homeowners reported sleeping under a net all off time and overall the occurrence of malaria and dengue were reported to have reduced since moving into the shelter. Loh-kat bucked this trend with just 20% reporting a reduction, possibly due to greater likelihood of gaps between elements such as walls and roofs.

The uptake of bed nets and their efficacy is the subject of numerous medical social studies and these results should be treated with caution as the surveys took place during the summer months where mosquitos are typically less prevalent. Geographical mapping of vector risk areas would need to be correlated with shelter locations, the condition of previous shelters, and statistical verification of self-reporting would all need to be addressed in order to draw any evidence based decisions from the data.

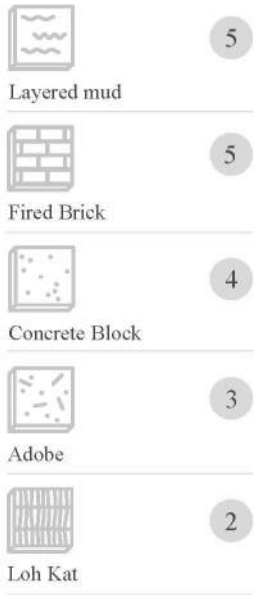


Figure X
Wall Topology Rank

8
Sustainable

8.1 Cost

Material Cost

Cost of construction is a key driver of shelter programme decisions for donors, agencies and homeowners alike. Cost of construction is in turn largely driven by materials for foundations, wall and roof.

Fired brick shelter are particularly expensive, driven in particular by cost of walls and foundations which are significantly more expensive than adobe, layered mud and loh-kat. Despite relatively less variation in roofing construction between the wall typologies, fired brick roofs were also found to be more expensive. It suggests that a decision to invest in fired brick walling is followed by greater investment in foundations and to a lesser extent roofing as well.

With costs determined through a variety of sources there are ranges for each material. For the cost analysis all of the BoQ's for adobe include fired brick lower walls, serving to push up the cost of this typology. This study considers adobe and layered mud to be within a range close enough to be considered more or less equal.

Where earth construction is to be stabilised it is significantly cheaper to use lime than Portland cement. For roof structure there is relatively little difference between timber and bamboo whilst steel is approximately 30% more expensive than timber. This uplift should be viewed in context of the small contribution that roofing makes to the overall cost of a shelter.

Key informant interviews reported greater demand contributing to price rises as well as profiteering from opportunistic vendors. One agency reported that poplar and bamboo prices rose by 150% in three years. Total construction costs rose by between 5 and 15% a year according to other agencies. Where provided, cash grants ranged from PKR10,000 up to 30,000, increasing to keep pace with inflation.

Primary roof structure	Cost (PKR)
Timber	11,410
Bamboo	12,071
Steel	14,736

Table 28 - Primary roof structure cost

Wall typology	Rank
Loh Kat	5
Layered mud	4
Adobe	4
Fired Brick	2
Concrete Block	2

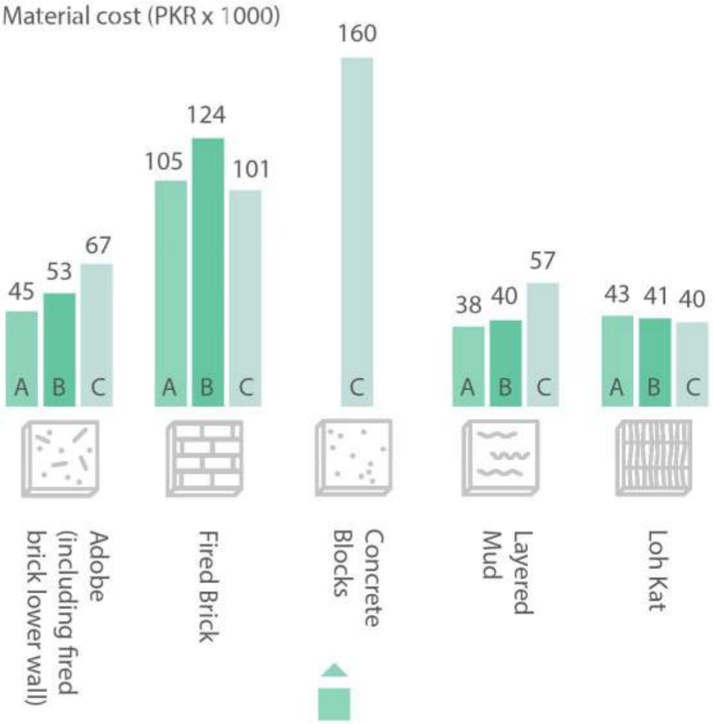
Wall Topology Rank
Material cost

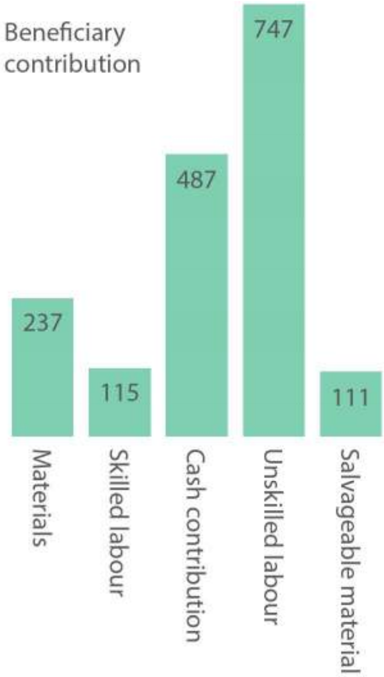
Construction	Cost/PKR		
	Unstabilised	With Lime (14% by volume)	With Portland Cement (9% by volume)
Layered mud/m^3	170	422	1,570
Adobe block/m^3	350	450	1,590
Plaster/m^2	4	14	96

Table 29 - Lime vs cement cost

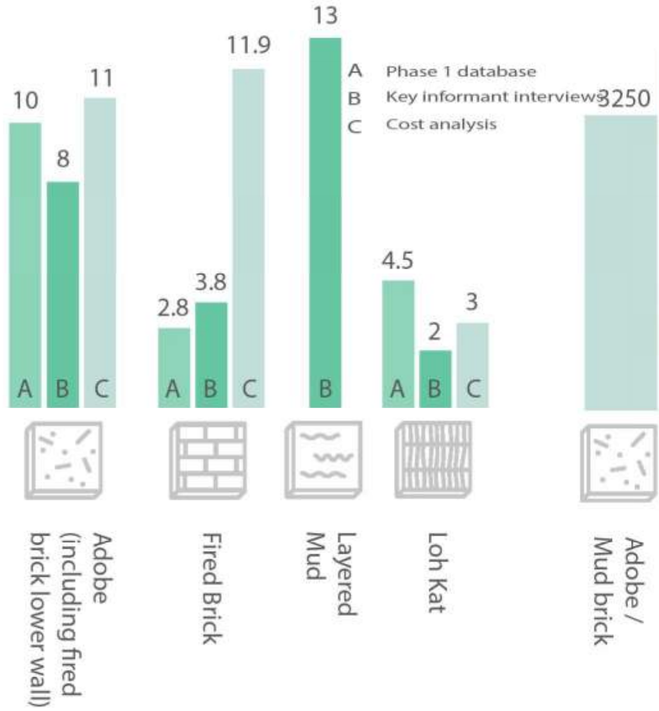
Cost

Material cost (PKR x 1000)

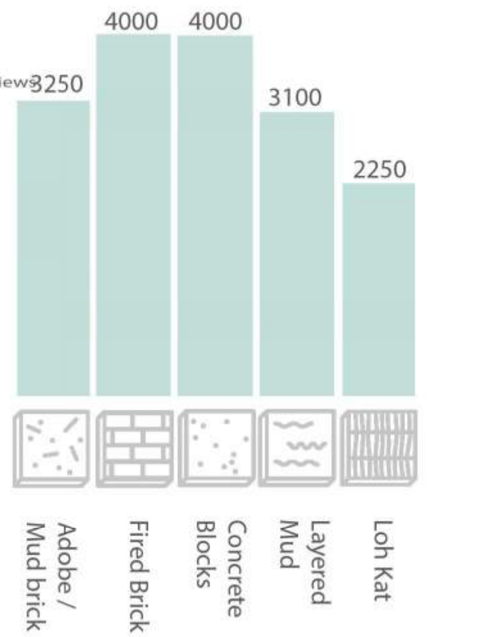




Labour cost (PKR x 1000)



Average cost of maintenance per year (PKR)



424PKR

Average monthly cost of lighting

11,524PKR

Average cost of modification to shelter

Labour Costs

Labour costs are divided between skilled and unskilled labour, with skilled labourers commanding an average daily wage of 790PKR and unskilled labourers, where paid, commanding 400PKR, which was just above the average income of 325PKR. Typologies requiring greater skilled labour are likely to incur greater labour costs as they incur greater wage costs but also reduce scope for communities to donate unskilled labour. In this way maximising unskilled labour can pay a duel dividend and may explain why fired brick came out as most expensive. Accurate comparison of labour costs is complicated however by varied labour contribution from beneficiaries and communities with inconsistent data gathered for Loh-kat in particular. According to Key informant interviews up to 50% of total labour days were donated, with 747 of 800 homeowners contributing unskilled labour and 115 contributing skilled labour. Labour costs comprised between 13% and 30% of construction cost, with 30% a commonly used rule of thumb for construction projects.

Life Cycle Cost

Life cycle costs are any costs incurred in the operation and maintenance of a shelter after it has been constructed. Considered with the construction cost and over the lifespan of the shelter they can provide a true picture of total cost allowing comparison between shelters over long periods of time.

However the design life of a shelter therefore has a very significant impact on the lifecycle cost, and with a range of values reported by shelter agencies (See section 6.1 – durability) the results are not considered reliable enough on which to compare the typologies.

Despite requiring less frequent maintenance homeowners reported spending more per year on fired brick and concrete block shelters, compared to the other wall typologies. Whilst initially surprising this could be a reflection of the 30% greater incomes that fired brick homeowners enjoy compared to loh-kat homeowners. The greater permanence of a fired brick shelter may also serve to encourage investment, although this hypothesis is unproven by this research.

Encouragingly the lowest annual maintenance bills were reported by homeowners of lime stabilised earth construction, suggesting a return on the initial investment in construction.

Operational costs for simple shelters are low, with an average spend of 424KR, or just over one day's salary, per month on lighting.

Loh Kat	5
Layered mud	5
Adobe	5
Fired Brick	2
Concrete Block	*

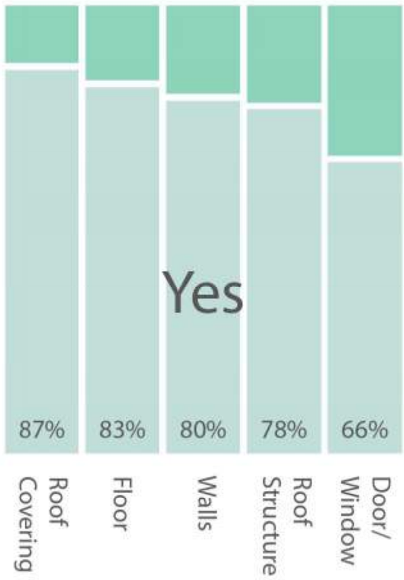
Wall Topology Rank
Labour cost

* *No data*

Supply chain

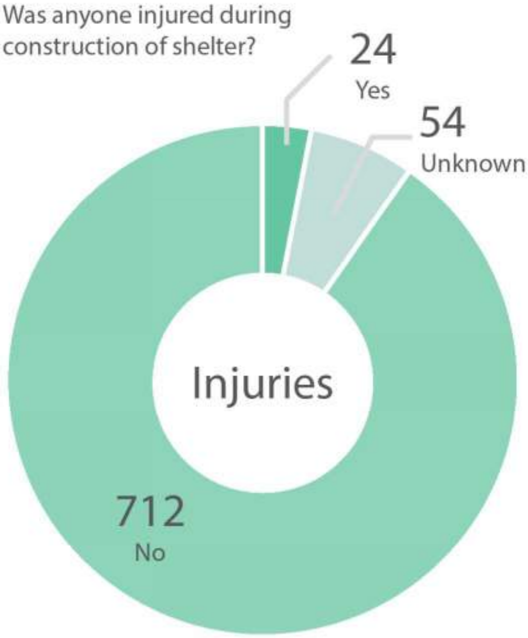
	Average distance to materials	Percentage say easy to obtain
Loh Kat	Within 7km	80%
Fired Brick	Within 9km	68%
Adobe	Within 4km	88%
Layered Mud	Within 4km	94%
Concrete Block	Within 14km	28%

Were the following shelter components easy to obtain?

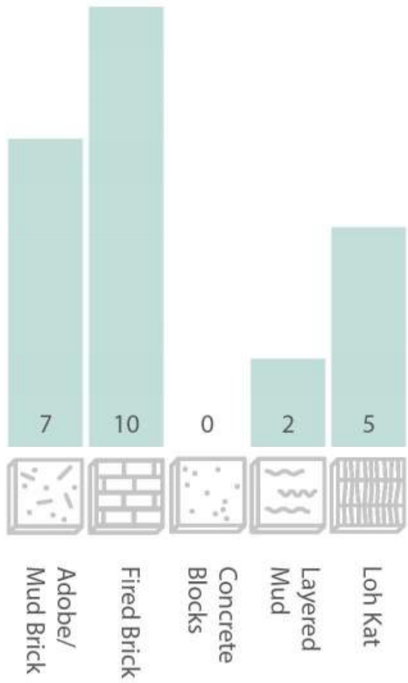


Roof structure material - average distance (km)

Was anyone injured during construction of shelter?



People Injured vs Material



3%
of homeowners reported sustaining injuries

3%
of UK construction workers report sustaining injuries

8.2 Local Supply Chain

Availability of Materials

Material availability is fundamental to shelter design and is considered by this study to be a function of distance and mode of travel to procure them. Overall the homeowners reported a positive picture with 70% to 80% of all materials reported as "easy to obtain" with average distances ranging from 5 to 15km indicating that shelter designs utilised appropriate materials. 15km is manageable with motorised transport representing a 1hr roundtrip at 30kph, but would exclude half (52%) of homeowners who reported no access to motorised transport, highlighting the limited means of the survey population.

Of the wall typologies concrete blocks were judged least easy to obtain with a correspondingly high average journey of 14km reflecting their relative scarceness in Sindh. Roof covering, floors and walls were judged easiest to obtain reflecting that they comprise primarily of earth with a source on average 4km away. Roof structure (bamboo, timber, steel) were sourced between 12 and 14km away. Doors and windows came last in terms of perceived ease of procurement, reflected perhaps in the remarkable number of shelters that remained without window or door coverings.

The metrics used for material availability might crudely measure resource depletion by proxy, with key informant interviews noting concerns that increased use of chicks was adversely affecting ecology. Shelter agencies also reported that there is little timber or branches for traditional loh-kat construction left in the Sindh, and that homeowners did not wish to cut down "productive" trees (e.g. mango) for the purposes of construction. This drove a switch to bamboo, the quality of which reduced over time as farmers sought to maximise production to meet increased demand by harvesting immature bamboo.

Layered mud	5
Adobe	5
Loh Kat	3
Fired Brick	2
Concrete Block	1

Wall Topology Rank
Availability

Labour Standards

Labour standards were included in the criteria as child labour was a known issue in brick kilns. This was subsequently broadened to include health and safety on site and benchmarking of cash for work schemes against average equivalent wages. Cash for work schemes paid 1.2 times the average salary (see section 8.1), ensuring that beneficiaries were not left out of pocket.

All of the shelter agencies interviewed reported having child labour policies in place, with varying degrees of monitoring to verify implementation, in some cases this simply included avoiding the use of fired bricks. To monitor all aspects of the supply chain is a sizeable undertaking and it was not possible to confirm the effectiveness or enforcement of these policies as part of this research. Where homeowners children took part in construction this was typically exempt from policy, a reasonable exclusion.

The number of injuries reported by homeowners is within acceptable limits and is coincidentally equivalent to the UK construction sector, which has more developed health and safety culture but includes more complex and risky activities when compared to construction of a single storey one room shelter. This data should be treated with caution as it is likely that injuries are underreported (Shelter Centre 2014). Injuries should be monitored and recorded to understand what the injuries are, their severity and what caused them. Potential risks from shelter construction include falls from height when erecting a roof, lime/cement burns and heavy lifting.

Loh Kat — 5

Layered mud — 5

Adobe — 5

Concrete Block — 5

Fired Brick — 1

Wall Topology Rank
Labour Standards

8.3 Natural Resources

Recycled / Reused

Whilst the concepts of recycling vs reuse of materials were not well understood in the homeowner surveys, just five reported materials from construction going to waste.

Most agencies reported utilising salvage from damaged shelter, with quantification of what was available one of the initial steps in community engagement. Windows and doors and to a lesser extent roofs were most likely to be re-used with agencies estimating between 2% and 20% of shelters including salvaged materials in this way.

Diesel and red oxide paint are among toxic treatments used to preserve bamboo and or timber. In both cases their impact on durability is minimal (see section 6.1) whilst posing a potential risk to those using them and the environment once they are disposed of. For these reasons it is recommended that their use is discontinued for treatment of timber and bamboo.

Embodied Carbon

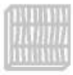
The sustainability analysis has shown that embodied carbon is concentrated in the wall material (66%), followed by foundations (21%) whilst the roof typically contains very little (9%). Of the wall typologies, fired brick contains a particularly high concentration of carbon equating to 556kgCO2/m2, exceeding the embodied carbon in the construction materials of a typical low-rise UK steel/concrete framed building. When making comparison it should be noted that a UK building will be designed to last at least 50yrs whilst a drive to improve the sustainability of the construction industry has seen embodied carbon in construction fall.

In contrast to fired brick loh-kat contains very little embodied carbon, whilst adobe and layered mud fall somewhere between. Concrete block, unhindered in this instance by lack of survey data, does well in comparison to fired brick and contains approximately one third more carbon than an adobe or layered mud shelter.

The high embodied carbon of fired brick is driven by the energy intensive and often inefficient timber fired kilns which contribute to deforestation. Where fired bricks are chosen alternative fuels can reduce pressure on timber and improved kilns can reduce embodied carbon through improved efficiency.

Where earth construction is stabilised with either lime or cement the decision will have a significant impact on the carbon footprint of the wall, with Portland cement stabilised adobe and layered mud containing approximately twice the carbon that if stabilised with lime. Comparison between common primary roof structures shows that bamboo has 23% less embodied carbon than timber, and 38% less than steel.

Whilst not accounted for in this study lime and timber are both known to absorb carbon over their lifetime in a process known as sequestration, serving to improve their green credentials.


5
Loh Kat


4
Layered mud


4
Adobe


2
Concrete Block


1
Fired Brick

Wall Topology Rank
Embodied Carbon

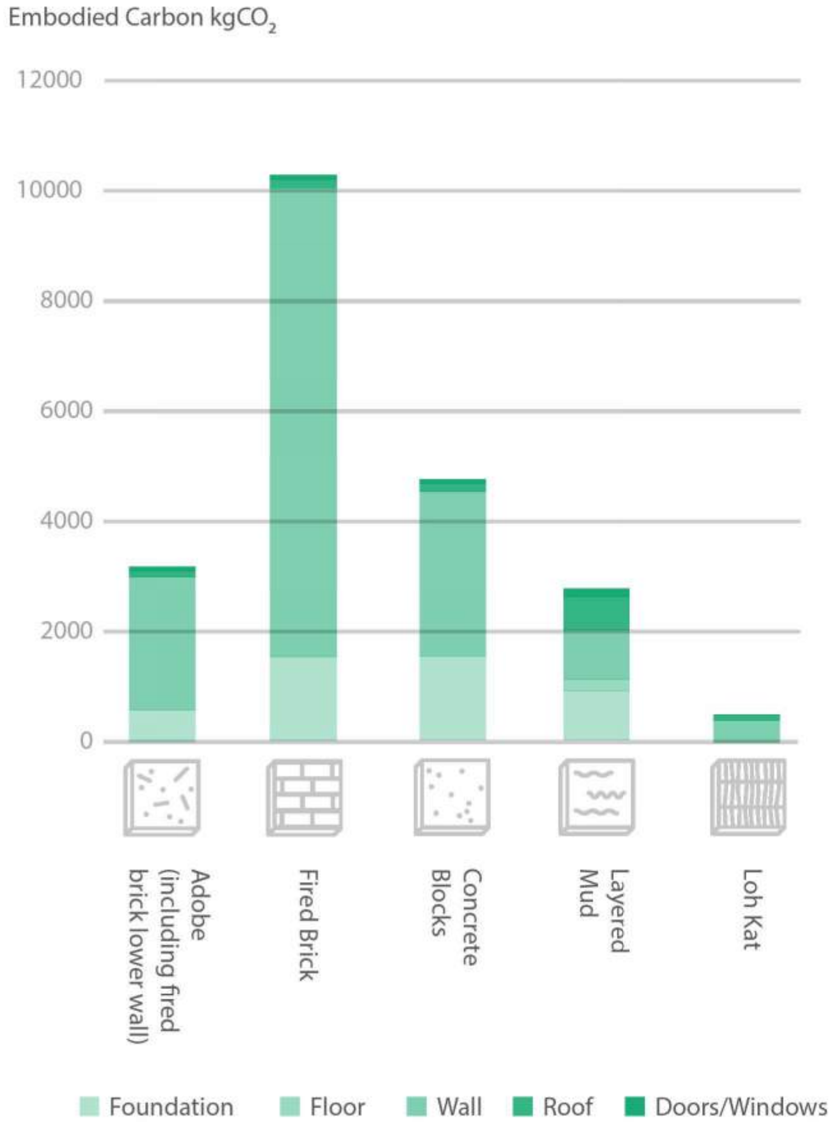
	KgCO2
Timber	311
Bamboo	241
Steel	390

Table 30 - Embodied carbon of primary roof structure

Construction	Cost/PKR		
	Unstabilised	With Lime (14% by volume)	With Portland Cement (9% by volume)
Layered mud/m^3	0	56	115
Adobe block/m^3	0	56	115
Plaster/m^2	0	1.3	6.5

Table 31 - Embodied carbon of earth stabilisation

Natural Resources



Were any materials left after construction?

9
Recommendations for further work

Self-recovery

The shelter community is increasingly focusing on how to reach those who self-recover following a disaster, with thinking currently being led by the Shelter Cluster Building Back Better Technical Working Group. Whilst the shelter guide is written for technical staff of shelter agencies it is anticipated that the recommendations for flood resilient shelter are equally applicable to self-recovery. In order to reach a wider audience, the key messages would need to be further distilled and repackaged. For example, training for trainers targeting community based organisations.

Quality assurance of design drawings

The study has illustrated that sub-standard drawings/designs lead to sub-standard shelter. Whilst the Shelter Guide provides quality assured designs for flood resilience in Sindh future crises in other regions will similarly require quality assured designs. A process is needed for generation of common quality assured designs or review and approval of shelter agencies own designs. For example, a review and approval process could involve drawings being submitted to the shelter cluster lead, who would then ensure that they satisfy a checklist of requirements, such as that developed for the structural analysis study (see section 4.2).

Probabilistic flood hazard study for land use planning in Pakistan

Available flood hazard data uncovered by this study consists primarily of flood extents maps as well as more detailed data from barrages on the Indus, such as flow speeds. A hazard study is required to review available data and identify the gaps, conduct hydrological modelling and understand changing weather patterns. This should inform production of probabilistic hazard maps that illustrate severity as well as likelihood of future flood events inform regional food risk management strategies and land-use planning.

Flood damage assessment methodology

Barring a couple of notable exceptions (UN-HABITAT 2010, Heritage Foundation 2013) this study was limited by a lack of data on the impact of flooding and heavy rain on shelter. This is perhaps a reflection on the lack of standardised methodology for collection of data on flood damage to buildings in general. This stands in contrast to post earthquake scenarios where both short and long form assessments exist, with the short form ATC-20 (https://www.atcouncil.org/atc-20) in common use around the world. There is a need for a standardised rigorous methodology to collect data on flood damage to vernacular construction in particular.

Further flood and rain testing

The scope of the flood and rain testing warrants a more detailed description than can be provided within this report. It is the intention that the methodology and findings will be published in full in a scientific journal in due course. For example, does loh-kat made from bamboo with chick matting perform better or worse than traditional loh-kat (woven branches) when subject to standing water?

Seismic hazard

Whilst this research addresses flooding, which is the primary hazard, the study area is also at risk from medium seismic hazard (see Appendix C). Non seismic structural evaluation of the shelter constructed following the 2010-2012 floods revealed that basic detailing such as ring beams were omitted, suggesting shelter would perform poorly in an earthquake. Existing guidance for seismic resistant shelter tends to cover areas of high seismicity resulting in recommendations for high levels of seismic detailing. There is less guidance available for how to build for medium seismic hazard. Further work is required to confirm the seismic hazard in the area, seismically evaluate existing shelter to determine likely performance against the hazard and make recommendations for how to improve shelter performance. This could include shake table testing at a local university.

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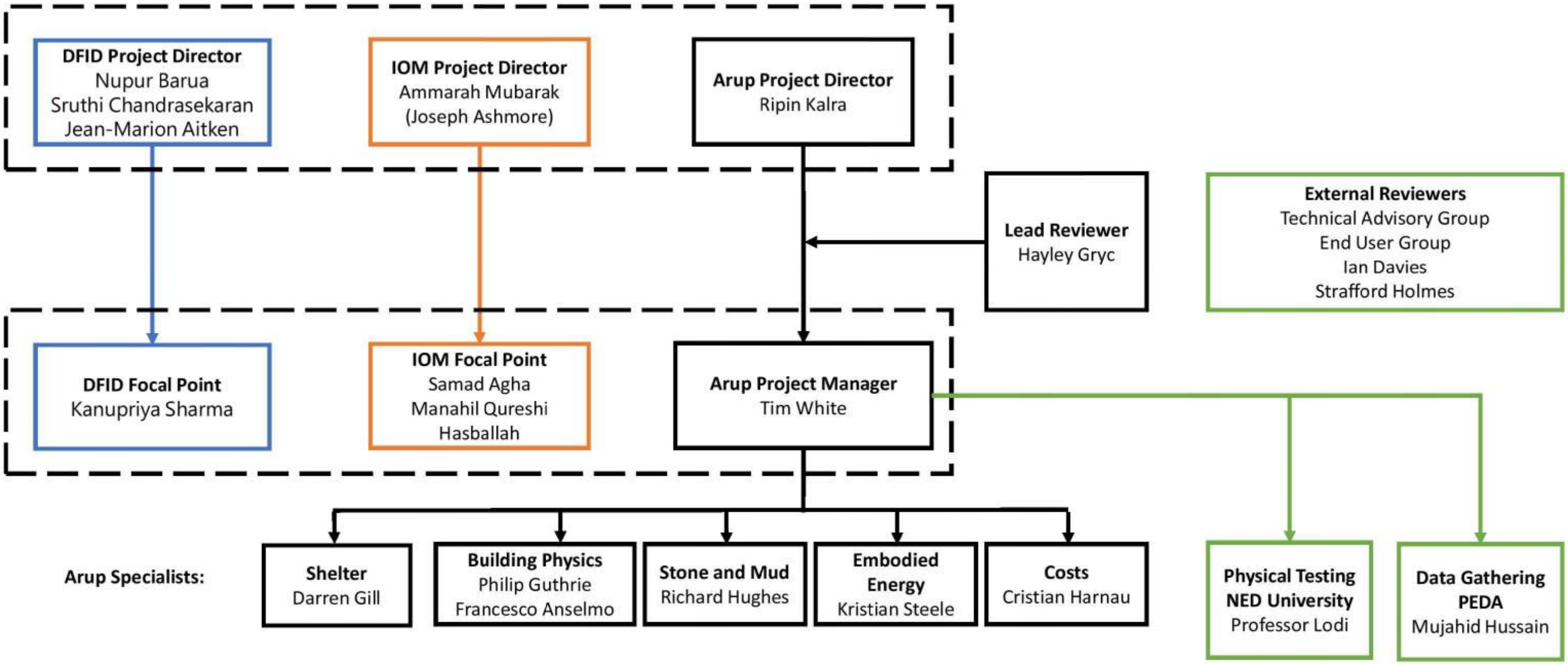
Appendix A

Team Organogram

Phase II Research for Improved Shelter Responding to Floods in Pakistan Organogram



Appendix B

Shelter performance key criteria with metrics

Criteria	Indicator	Variable	Qualitative Metric	Quantitative Metric	Baseline	Source
Safe and resilient	Material quality	Compatibility	Are the materials used compatible with each other?	N/A	Fired brick and concrete block to be used with cement or lime mortar and plaster Stabilised soil walls to be used with stabilised soil mortar and plaster Foundation material to be at least as strong/water resilient as the walls Designs in shelter guide will use compatible materials	Phase 2 Research - Physical testing shows the mud mortar and unstabilised mud foundations undermines fired brick investment
		Durability	Will the materials reach their intended design life? Are timber and bamboo adequately treated? **Loh-kat** Are timber and bamboo elements raised above the floor?	What is the intended design life?	The first step is to set a design life that is acceptable to the donor/agency/homeowner respecting ability to maintain Best practice detailing – e.g. raising bamboo and timber off the ground	
		Specification	Are materials adequately specified? Are quality control procedures specified for mix, manufacture and curing?	**Load bearing construction:** Is the compressive strength equal or greater than recommended? (In practice it is unlikely that material strength will be known, but low tech field tests are available)	Bamboo and timber treatment (specified in guidance) **Loadbearing construction** Suggested brick strengths for loadbearing construction are: 2.5N/mm2 (non seismic)	
	Stability and Integrity	Foundation depth	Are the foundations founded on firm ground? **Loh kat** Are the verticals embedded deeply enough to prevent rotation?	**Loadbearing construction:** How deep are the foundations embedded into undisturbed ground?	Firm ground may be assessed using rules of thumb for both clay and sandy soil. Loose sand is easily dug with a shovel but dense sand requires hard-digging for the excavation 0.75m (minimum)	Phase 2 Research - Structural analysis (Shelter Cluster Pakistan 2012, UN Habitat 2015)
		Foundation width	N/A	**Load bearing construction:** How wide are the foundations?	**Load bearing construction:** at least 0.5m or 2x wall thickness	Phase 2 Research - Structural analysis (UN Habitat 2015)
		Stability and slenderness	**Frame:** Do the arrangement of horizontals, verticals and bracing provide adequate stiffness? Is an adequate number and means of connection between the frame elements provided?	**Loadbearing Construction:** Is the slenderness of the wall panels within recommended limits?	**Loadbearing:** Refer to slenderness limits summary table Piers provide added stability **Frame:** Connections should prevent relative movement and rotation of the vertical and horizontals Diagonal bracing is required in walls and roof	(Walker, P. HB195-2002, UN Habitat 2015, Bureau of Indian Standards IS 13827-1993)
		Openings	N/A	**Load bearing construction:** Are the size of the openings within the allowable limits? What are the distances between openings (windows/doors)? What are the distances between openings and the end of the wall? Do the lintels extend the correct distance past the opening?	Refer to shelter guide for opening limits Lintels should extend at least 300mm beyond the edge of an opening	(Walker, P. HB195-2002, UN Habitat 2015, Bureau of Indian Standards IS 13827-1993
		Connections and tying	**Roof structure:** Is the roof structure adequately connected together? -roof covering to secondary roof beams -secondary roof beams to main roof beams -main roof beams to the top of the wall **Loadbearing:** Are masonry leaves fully bonded together? Are the junctions and corners of walls fully bonded? Are ring beam(s) provided and are they continuously connected along their length and at corners also? **Seismic:** Are sufficient tie beams provided? Is the roof able to hold the walls together by acting as a diaphragm?	**Roof structure:** What load (kN/m2) are the roof connections able to withstand? -roof covering to secondary roof beams -secondary roof beams to main roof beams -main roof beams to the top of the wall **Seismic:** Roof to wall connections designed for seismic tie force Ring beam can take seismic tie force	**Roof connections:** Roof connections are able to resist an uplift load of 2.5pa (coastal) and 1.6Kpa (inland) applied to the overhang **Loadbearing:** All loadbearing masonry should have a ring beam at roof level. Ideally this should align with the top of the windows so as to also act as a lintel. A concrete ring beam should be 150mm deep minimum and the same width as the wall. **Seismic** Ring beams should be provided a roof, cill and foundation level In plane roof bracing or similar should be provided to stiffen the roof and hold the walls together	(Ministry of Housing and Works 2007)
		Roof capacity	Is the roof able to withstand loading from saturated soil during heavy rain? Is the roof able to withstand loading from people/belongings/livestock if used as safe refuge?	What load (kN/m2) is the roof designed for?	Roof should be able to take 2.5kN/m2 saturated soil load Roof should be able to take additional 0.6kN/m2 live load to be used as safe refuge	Phase 2 Research - Structural analysis
		Elevated ground	**Standing water:** If the shelter is on elevated ground is it above past/future flood events?	**Standing water:** What height is the surrounding ground level above natural surface level (NSL)?	Maximum practical platform construction level is ~1'6"	

Criteria	Indicator	Variable	Qualitative Metric	Quantitative Metric	Baseline	Source
	Water resilience	**Raised floor**	**Standing water:** If the shelter has a raised internal floor level is it above past/future flood events?	**Standing water:** What height is the internal floor above the Natural Surface Level (NSL)?	Maximum practical raised floor level is ~3"	
		Waterproof materials	**Standing water:** Are the foundations built from waterproof materials? Are waterproof materials used up to the past/future flood level? Earth construction may be tested by immersing a block in a bucket of water **Loh Kat:** Are frame structures able to withstand immersion?	**Standing water:** To what height are the materials used waterproof?	**Loadbearing construction:** materials must be waterproof to level above flood otherwise the structure will fail. If left in a bucket of water they should remain intact **Loh-kat:** Frame to be constructed of rot resistant timber/bamboo	Phase 2 Research - Data Gathering and Physical testing
		Sacrificial protection	**Heavy rain:** Are the outsides of the walls plastered? If mud plaster is used has it been stabilised? If a mud roof is used has it been stabilised? If using earthen walling is sacrificial mass provided at the base of the shelter? Is the sacrificial mass stabilised?	N/A	Walls should be plastered to provide a sacrificial wearing layer that can be repaired without the wall structure being damaged Earth plasters that are stabilised with lime or cement will require less frequent repair Sacrificial mass in the form of 'toes' provided at the base of a shelter will protect the base against heavy rainfall	Phase 2 Research - Data Gathering and Physical testing
		Overhangs	N/A	**Heavy rain:** Are the tops of earthen walls protected by a roof overhang?	0.3H overhang (roof connections must be designed for uplift from wind)	(Walker, P. HB195-2002, Houben, H and Guillaud, H. 1994)
		Drainage	**Heavy rain:** Is the base designed to prevent standing water? Is the roof designed to prevent standing water? If a mud roof is used has it been stabilised?		The base of a shelter should slope away from the walls Roof drainage details are included Adding lime to a mud roof will improve its water resistance, improving drainage by reducing water seeping it	
	Buildability, maintenance and modification	**Communication**	The design information is complete and communicated clearly		Design information should include a complete set of annotated and dimensioned drawings (Plans, sections, elevations, connections are detailed) and a full material specification	Phase 2 Research - Structural Analysis, Design Information Review
		Buildability	Are construction defects present? (caution: need to avoid confusion with defects from poor design or substandard materials) Are the techniques and methods used locally familiar? Is specialist training required? (e.g. use of lime) Does the design require construction of complex details? Is the design or aspects of the design replicable at a local level?	How long does it take to construct?		Phase 2 Research - Data Gathering
		Tools	Does the homeowner have access to the tools required to construct, maintain and modify their shelter?		Power tools are unlikely to be available (drills, welding equipment)	Phase 2 Research - Data Gathering
		Skills availability	Does the shelter require skilled and or unskilled labour to construct, maintain and modify? Are the skills required available locally?		Shelter than can be rapider and maintained without skilled labour will be cheaper and easier to look after.	Phase 2 Research - Data Gathering
		Training	Was training provided to the local community?		Training should cover construction, maintenance and repair and modification Training is essential where soil stabilisation is required.	Phase 2 Research - Data Gathering
		Maintenance	N/A	How many times a year does the shelter require maintenance?	Typically once every 2 years, or after particularly heavy rain	Phase 2 Research - Data Gathering
		Modification	What modifications may the community wish to make in the future? Can they be made without compromising the performance of		Safe addition of veranda to be considered in design	Phase 2 Research - Data Gathering

Criteria	Indicator	Variable	Qualitative Metric	Quantitative Metric	Baseline	Source
Acceptability	Comfort	Thermal Comfort	Does the shelter provide adequate protection from extremes of temperature? Does the shelter design prevent direct sunlight entering? Are any measures taken to reduce incident solar gain? Does the occupant feel comfortable in the shelter?	Is the internal air temperature close or equal to external air temperature in the shade? Is the internal operative temperature less than the external air temperature in the shade?	Internal air temperature to be equal or close to external air temperature in the shade Internal operative temperature to be less than external air temperature in the shade by Openings are shaded from direct sunlight Internal surface temperatures are reduced by maximising roof and wall thickness	Phase 2 Resaerch - Thermal Analysis
		Ventilation		Does the size and location of openings maximise ventilation?	Opening size and location: Two ventilation openings of a combined area of least 2% of the floor area of the shelter, one at high level, one at low level, one on a north facing wall the other on a south facing wall	Phase 2 Resaerch - Thermal Analysis
		Lighting	Does the shelter prevent direct sunlight from entering? Does the shelter have adequate natural light during the day to undertake household tasks? Is the homeowner able to view outside?	What % of the shelter has illuminance between 200 and 100 lux between the hours of 9am and 5pm over the course of a year? How many windows does the shelter have and what is the opening area?	Direct light should be prevented from entering the shelter Shelter has at least one window opening of 0.6x0.9m (this should achieve useful daylight illuminance 70% of the time) Homeowner should be able to view outside	(Reinhart C et al. 2013, Mardaljevic, J., et al. EPFL-CONF-166212. 2011)
		Waterproofing	Do the roof and walls keep the homeowner dry?		Roof and walls should keep the occupants and their belongings dry	
	Space	Size	Does the shelter provide sufficient covered space to provide dignified accommodation?	Is the floor area (m2) per person at or above the recommended minimum?	3.5m2 (37.5ft2) / person)	(Sphere Project 2004)
		Layout and flexibility	Is the plan shape appropriate for the local culture? Is the homeowner able to use the space as they wish?	N/A		Phase 2 Research - Data Gathering
	Protection	Security	**Personal security:** Is the homeowner able to secure door and window openings from the inside? Is the wall and roof construction secure? **Possession security:** Is the homeowner able to secure door and window openings from the outside? Is the wall and roof construction secure?	N/A	Windows can be bolted or easily secured from the inside. Doors can be bolted or easily secured from the inside. Doors can be locked from the outside. Walls and roof can not be broken through.	Phase 2 Research - Data Gathering
		Privacy	**Visibility:** Is the occupant afforded privacy against visibility through openings? **Acoustics:** Is the occupant afforded with acoustic privacy?	N/A	Door and window covers are provided/added Curtains are provided/added Window openings are private by design (eg hit & miss brickwork) Walls are thick enough to provide acoustic privacy	
	Health & Safety	Internal air quality	Does the shelter design maintain air quality whilst cooking, either inside or outside?	Are particulate levels within acceptable limits? Are carbon dioxide levels within acceptable limits?	Open fires should not be lit inside a shelter as it is not practically possible to maintain acceptable air quality through natural ventilation. If cooking inside a smokeless stove should be used. ASHRAE limits carbon dioxide levels to 1000-1200 parts per million.	(ASHRAE 62.1-2010)
		Fire Hazards	Are sources of fire ignition kept away from the shelter? Is the use of combustible materials kept to a minimum?	Is the separation between shelter equal or greater than recommended?	If cooking inside a smokeless stove should be used. 2m minimum distance between shelters. This may be reduced for masonry block shelters without combustible walls	(Sphere Project 2004)
		Vector Control	Are openings protected with mesh? Alternatively do the occupants sleep under nets?	N/A	Plastic or metal mesh over openings And/or Sleeping nets are provided	
	Cost	Materials	Is the shelter affordable for donors/agencies? Is the shelter comparable in cost to non agency built shelter? Are DRR features affordable and do they provide value for money?	How much do the materials cost?	Fired brick = 10,000 to 12,000PKR Adobe, Layered mud, Loh kat = ~4,000PKR	Phase 2 Research - Data Gathering and Cost Analysis
		Labour		How much does labour cost? What percentage of construction cost is labour?	15 - 30% of material cost Provision of unskilled labour by the community reduces cost, provides training opportunities and improves capacity to maintain shelter	Phase 2 Research - Data Gathering and Cost Analysis
		Life cycle	Is the cost of operation and maintenance affordable for the homeowner?	How much does operation cost per year? How much does maintenance cost per year? How much does operation/maintenance cost as a percentage of income?		Phase 2 Research - Data Gathering

Criteria	Indicator	Variable	Qualitative Metric	Quantitative Metric	Baseline	Source
Sustainability	Local Supply chain	**Availability of materials**	By what means do homeowners travel to obtain materials for minor repairs? By what means do homeowners ravel to obtain materials for more significant repairs?	How far do homeowners have to travel to obtain materials for minor repairs? How far do homeowners have to travel to obtain materials for more significant repairs?	Regular maintenance < 5km (walking) Engineered items < 10km (motorised) Shelters utilising fewer engineered materials (sawn timber, steel, etc.) are likely to benefit from greater material availability Likewise for shelters utilising fewer depleted materials.	Phase 2 Research - Data Gathering
		Labour standards	Do suppliers have a child labour policy? Does the implementation agency have a child labour policy? Are mechanisms in place for recording cause and severity of injuries?	How many injuries were reported during construction? Are cash for work schemes equivalent to typical daily wages from main source of employment?	Agencies and their suppliers should have child labour policies in place and checks and balances to verify their implementation Cash for work average per day = 400PKR Average income per day = 330PKR Health and safety to be included in training programmes	Phase 2 Research - Data Gathering
	Natural resources	**Recycled/ Reused**	In the case that the homeowner wishes to demount the roof is this included in the design? Do timber/bamboo/steel treatments avoid the use of toxins?	N/A	Roof connections allow roof to be demounted if required by homeowner Avoid use of diesel and other toxic timber/bamboo treatments	Phase 2 Research - Data Gathering and Sustainability Analysis
		Embodied Carbon	N/A	How much embodied carbon is required for construction? How much embodied carbon is required in operation?		Phase 2 Research - Sustainability Analysis

Appendix C

Context

Geology of the Sindh

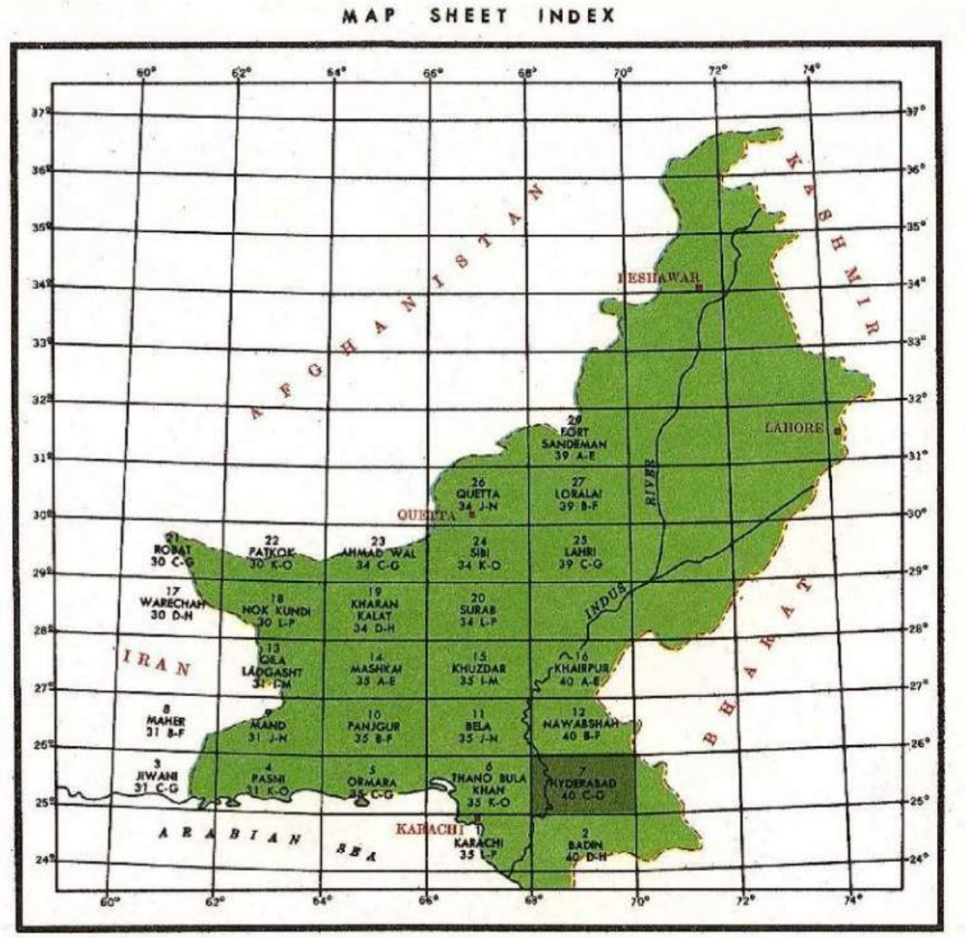
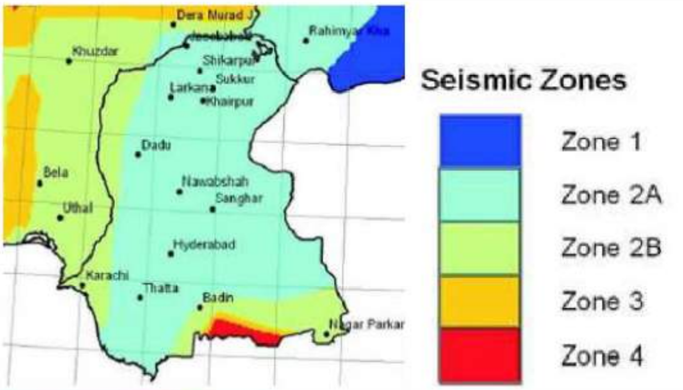


Figure 1 - 1:250,000 scale geological map index sheet

Figure 2 - Extract from 1:250,000 scale geological map Sheet 16

Seismic hazard

A recent study of the area (http://www.emme-gem.org/) suggests that seismic hazard in the area is underestimated by the Pakistan Building Code (Ministry of Housing and Public Works 2007), with average peak ground acceleration in the area underestimated by 25%. UN Habitat guidelines for flood resistant housing are reportedly suitable for up to Zone 2B of the Pakistan Building code, PGA* of up to 0.2g.

<table>
<tr><td>Source</td><td colspan="2">Hazard (Peak ground acceleration)</td></tr>
<tr><td>Pakistan Building Code</td><td>Typical study area PGA = 0.16g
Maximum PGA = 0.3g</td><td>
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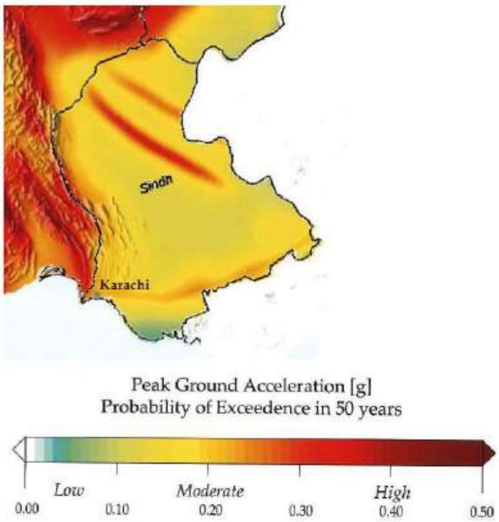
<tr><td>EMME study</td><td>Typical study area PGA = 0.2g
Maximum PGA = 0.3g</td><td>
</td></tr>
<tr><td colspan="3">*Note: Peak ground acceleration is a measure of an earthquake amplitude often expressed as a fraction of acceleration due to gravity (g) = 9.81m/s^2</td></tr>
</table>

Appendix D

Data gathering

Appendix E

Physical testing

Appendix F

Analytical desk studies