WORCESTER POLYTECHNIC INSTITUTE

Developing Smart Origami Shelters for Himachal Pradesh

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Developing Smart Origami Shelters for Himachal Pradesh

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Abstract

This project applied the principles of origami to develop smart shelters that can be adapted for individuals or groups in Himachal Pradesh, India. We engaged diverse user groups, including slum residents, migratory construction workers, and trekkers in the design process to develop a versatile structure that is portable, deployable, and weather resistant. The final product was field-tested among those same user groups to produce a list of additional features and changes to make in future versions.

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Section	***Authors***
Abstract	Neneh Switalla, Benjamin Pulver
Introduction	Benjamin Pulver, Neneh Switalla, Samantha Chernin, Isamu Nakagawa
Origami as a Design Foundation	Benjamin Pulver, Neneh Switalla, Samantha Chernin, Isamu Nakagawa
Materials and Assembly in Shelter Design	Benjamin Pulver, Neneh Switalla, Samantha Chernin, Isamu Nakagawa
Site Specific Considerations	Benjamin Pulver, Neneh Switalla, Samantha Chernin, Isamu Nakagawa
Increasing Functionality for Extended Use	Benjamin Pulver, Neneh Switalla, Samantha Chernin, Isamu Nakagawa
Methodology: Creating Shelters for users in Himachal Pradesh	Benjamin Pulver, Neneh Switalla, Samantha Chernin, Isamu Nakagawa
Results	Benjamin Pulver, Neneh Switalla, Samantha Chernin, Isamu Nakagawa
Discussion	Benjamin Pulver, Neneh Switalla, Samantha Chernin, Isamu Nakagawa
Project Outcomes	Benjamin Pulver, Neneh Switalla, Samantha Chernin, Isamu Nakagawa
Conclusion	Benjamin Pulver, Neneh Switalla, Samantha Chernin, Isamu Nakagawa
Poster	Isamu Nakagawa
Prototype Construction	Benjamin Pulver, Neneh Switalla, Samantha Chernin, Isamu Nakagawa, Siddhartha Gadipalli, Nitin Krishna

Table of Contents

The case for better semi-permanent shelters in Himachal Pradesh

In 2015, a team of students undertook a design challenge to create a folding, lightweight temporary shelter suited towards the needs of a variety of stakeholders in and around Himachal Pradesh. The resulting cardboard and tarp prototype could fold flat for transport and expand dynamically to house up to two individuals. The use of cardboard however, while not unusual, was not ideal for long-term usage. In order to advance the idea, we engaged the users in the design process, explored better materials, and created and field-tested an improved prototype.

After feedback and field studies, the team determined that a majority of the target audience was looking for semi-permanent shelters rather than portable and lightweight structures (see Figure 1). In order to improve upon the existing structures used by stakeholders, the team solicited a range of requirements that the design should meet. The final shelter should withstand heavy rainfall, high winds, and snow accumulation. Additionally, it should have insulating properties, be fire resistant, and support for some form of lighting. These extra qualities reduce portability and increase cost, but also increase comfort during extended use. All of these features were combined into a structure that is compact when stored and can be rapidly deployed when needed.

Figure 1: Current shelters of homeless population in Himachal Pradesh.

The goal of this project was to manufacture an origami shelter that meets stakeholder requirements and features 'smart' technologies. To meet that goal, we identified four objectives:

1. Identify materials and manufacturing options for production
2. Engage in user-based design in collaboration with stakeholders
3. Produce 3 final products based on 1 initial prototype that meet the design criteria
4. Distribute prototypes to users to perform field-testing and gather feedback

Origami as a design foundation

The Japanese art of origami has been in practice since 105 CE (History of Origami, 2015). After studying the techniques and applications associated with origami, researchers and designers have incorporated these unique features into large-scale deployable structures. As the practice of folding techniques advanced, so has the scope of the feasible applications; today, these techniques are being used to improve cutting edge technologies including NASA satellites, robotics, airbags, heart stents, and retinal implants (Main, 2014). The use of origami principles in these advanced fields indicates its versatility as a viable construction technique for shelters (Rihal, 2013).

The basic folds of origami most often used in disaster relief shelters today include the Miura-Ori pattern, Yoshimura/diamond pattern, and the reverse fold (see Figure 2). Rihal chose the reverse fold and Yoshimura fold were due to their qualities of “significant lateral strength and stiffness in the longitudinal direction” (Rihal, 2013, p. 1086). Another

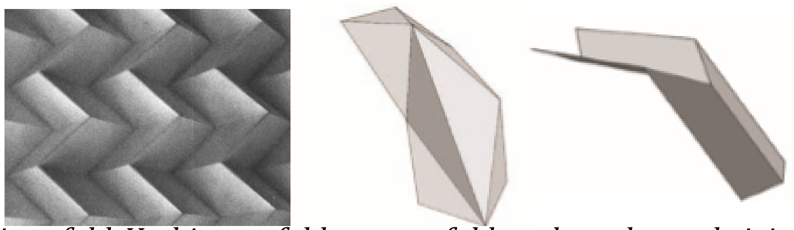

Figure 2: Miura fold, Yoshimura fold, reverse fold, and overlap style joints (Gattas & You 2016; Rihal, 2013).

important property of origami folds is deployability – the ability to quickly assemble on site and collapse for transport. From this perspective, the Miura-Ori fold is one of the best types of folds as it is easily able to compress into squares via orthogonal folding (Miura, 1994). Miura, the originator of the Miura-Ora pattern, explains in his 1994 work that this property is what makes the fold so deployable. This factor is why NASA has used the Miura-Ora fold in transporting satellites and why we felt it was appropriate for a compact semi-permanent shelters (Miura, 1994).

In terms of offering flexibility in modular unit expansion, the two simplest types of joints for connecting origami pieces are the overlap joint and the seam joint. The overlap joint provides the most strength and stiffness as the material itself provides the necessary support (see Figure 3) (Rihal, 2013). The seam joint simply connects two structures along a seam without overlap by adding additional material such as tape or fabric. The advantage of the seam joint is that it minimizes material waste and is more flexible than the overlap joint.

Figure 3: Overlap joint shown on a Yoshimura pattern (Rihal, 2013)

Materials and assembly in shelter design

To identify appropriate materials, we analyzed those most commonly used in existing semi-permanent shelters as well as other materials that meet design requirements but are not typically used in existing shelters. Material properties were taken from various materials databases, including CES EduPack 2015 (see Table 1 of Appendix A, Supplemental Materials).

There are, in general, three types of non-origami or simple origami shelters: soft-walled, clamshell, and rigid-walled accordion style (see Figure 4). Soft-walled shelters tend

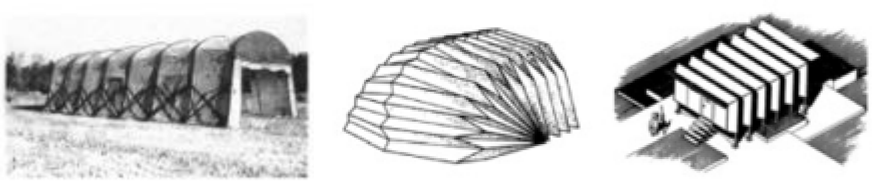

Figure 4: Soft-walled accordion, clamshell, and rigid-walled accordion style shelters (Thrall & Quaglia, 2014).

to be more adaptable and can be more easily compacted, but lack the rigidity necessary to be self-supporting (Thrall & Quaglia, 2014). This makes rigid-walled structures more suited towards permanent or semi-permanent housing and soft-walled structures more suited towards temporary shelters. Although origami can create complex structures, doing so with thicker materials becomes difficult because as the origami folding pattern increases in complexity the opportunities for misalignments increases. For this reason, simple folding techniques, such as the reverse fold, are best suited for this project. Two good examples of origami style shelters that use simple folding techniques are the Biodegradable Tent and the KarTent (see Figure 5). These shelters are designed for limited use by one or two individuals and are therefore not suited for extended use by families or other large groups. The key benefits of an origami shelter are deployability and rigidity, but these advantages do not scale well as the rigidity of a large scale origami shelter increases its weight and reduces the packing efficiency.

Figure 5: Biodegradable Tent (left) and KarTent (right) (Harden, 2015; KarTent, 2015).

Site-specific considerations

In response to origami's complexity, simple tent structures were initially explored to understand their limitations in the design challenge. Tents can be highly compact and lightweight (see Figure 6), and have the advantages of being highly portable, lightweight, and scalable. On a limited basis, for one or two individuals, tents are lighter and more compact than an equivalently sized origami shelter. Additionally, tents are soft-walled structures which make them more flexible and thus less prone to failure. However, we determined that they rely on expensive and highly specialized materials that are neither available nor affordable in Himachal Pradesh (Haist & Neale, 2015).

Figure 6: Double-walled tent, A-frame, tarp tent, and, pyramid tarp (Haist & Neale, 2015).

In Himachal Pradesh, there are specific user groups that require portable or improved housing. For example, Gaddi Herders, trekkers, and urban homeless require highly portable lightweight shelters (Andrews, Felix, Joshi, Mehta & Novinyo, 2015). Slum residents require more permanent housing which meets building permits, is heavier, and has additional features for day-to-day living. Although all of the potential users required some form of improved shelter, none of their requirements were perfectly matched with the benefits provided by an origami shelter. As discussed above, on a small scale, tents are lighter and more compact than origami shelters and thus are better suited to the needs of herders, trekkers, and the urban homeless. For more permanent residents, there is less need for rapid deployability and thus an origami shelter is a good, but not ideal, solution for this group of users.

Increasing functionality for extended use

In addition to meeting the basic requirements of the stakeholders, incorporating additional 'smart' technologies and adaptations that increase the quality of life of a user was a priority. Some of these technologies have been implemented in currently available shelters and thus it is important to review those implementations. Solar technology has long been added to tents in order to accommodate everything from recharging cellphones to powering refrigerators and generators. One example, the Cinch Tent uses solar panels attached to the roof to power recharging for devices and LED stakes and lanterns for convenience at night (Weiss, 2015). Other tents, such as the Kaleidoscope Tent (see in Figure 7) use solar fabric to create solar panels that bend with the shape of the tent (Solar Powered Tents, 2016).

Figure 7: The Cinch tent (left) and the Kaleidoscope tent (right) (Weiss, 2015; Solar Powered Tents, 2016)

With the addition of solar panels comes an ability to light the interior space at night. Recently developed to fill this need without high expense was the charity Liter of Light, which uses plastic bottles filled with bleach and water to refract both sunlight and the light of LEDs into the shelter (see Figure 8). When attached to a solar panel and sensor, this system can utilize sunlight during the day and the light of the LEDs at night. Simply installed in a hole cut into the ceiling, a one-liter bottle can light a 15 square-meter room at night. These lights last upwards of five years before the water needs to be replaced, while the LEDs have a lifespan of 70,000 hours (Williams, 2015).

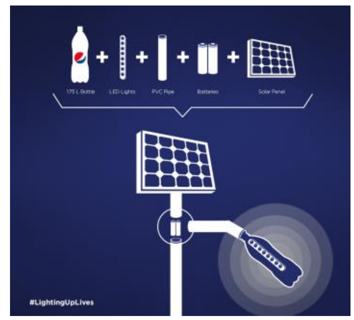

Figure 8: Liter of Light with solar panel (Zee, 2015).

Another feature that would be useful is the ability to collect water for drinking and other uses. This has been accomplished in two main ways for shelters: rooftop rainwater collection and solar stills. Basic catchment systems, such as tarps and plastic funnels, have been employed to catch rainwater on tents; these systems allow the majority of this water to be collected and stored for drinking or other purposes. One such method can be seen used in the Kammok Rain Tarp (see Figure 9). The Kammok tarp uses the natural curve of its shape as a catchment for rain water which it then funnels into a holding canister (Weiss, 2013)

Figure 9: The Kammok rain tarp (left) and water collection system (right) (Weiss, 2013)

For use during the dry season, a solar still can be added to the shelter. Solar stills are a method of water collection often used when there is not an abundance of rain. Based on the design of stills taught in the outdoor survival training used by the US Air Force, this still would be both simple and effective (Jones, 2016).

A final addition for long-term use of this shelter is an integrated storage system which makes use of space that would otherwise be lost due to the origami folds used in the shelter's construction. Based on similar principles to freestanding organizers built by Coleman, incorporating a flexible structure which compacts and expands with the shelter while utilizing the rigidity of the shelter as a frame (see Figure 10) would be ideal.

Figure 20: Coleman freestanding organizer (The Coleman Company).

In creating an optimal solution for a semi-permanent origami shelter, it is apparent that such a design should use simple folding techniques, feature a combination of materials to meet all desired requirements, use one or both of the simple joints to provide maximum support and flexibility, and incorporate multiple 'smart' features. A shelter that incorporates all of these features will not only meet the stakeholder requirements but will also be able to be efficiently manufactured.

Methodology: Creating shelters for users in Himachal Pradesh

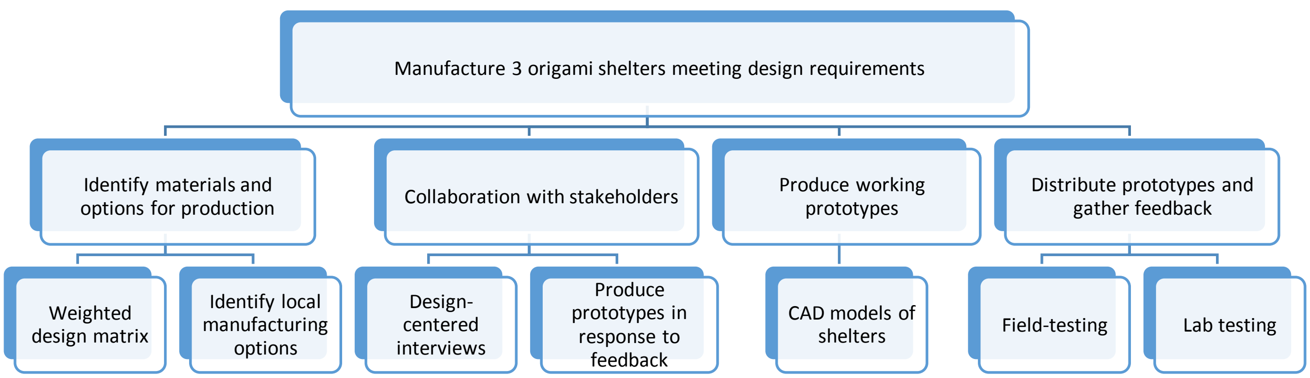

Figure 11: Methodological approach to the project

Objective 1: Identify materials and manufacturing options for production

We interviewed IIT-Mandi faculty experts in material science in order to identify a suitable materials database to use in order to select the materials that best fit the design requirements and were locally available. From there, materials were added to a weighted design matrix, and the materials which best fit the project were chosen. We also identified local manufacturing options, with a focus on cottage industry and personal manufacturing (see Appendix B, Supplemental Materials).

Objective 2: Engage in user-based design in collaboration with stakeholders

We revisited and completed the assessments of shelters from stakeholders initiated in a study from 2015. We conducted additional design-centered interviews and observations with groups of stakeholders; initially targeting potential users near Victoria Bridge and the IIT campus in Mandi. These interviews and observations were documented through handwritten and photographic records. This method engaged the users immediately through early direct contact, which was shown to be more effective than simply using them as design verification.

Objective 3: Produce 3 final products based on 1 initial prototype that meet design criteria

As part of the design and production of the shelter the team used SolidWorks to create a selection of potential designs; from that pool the best design was chosen for full-scale manufacturing. To compensate for having raw materials that were not necessarily as large as required, the team used a modular approach by connecting several pieces together with seam and overlap joints. Overall, the team sought to develop a total of four models: an initial prototype for field-testing followed by three final products with modifications based on feedback from testing.

Objective 4: Distribute prototypes to users to perform field testing and gather feedback

Field testing was performed in two parts: by bringing the prototype to users, and by performing laboratory testing to verify design specifications. We solicited a range of volunteers from both Mandi and Kamand, as well as from interested IIT and WPI students for field-testing of full-scale prototypes. Feedback from the field-testing was collected via interviews conducted by team members (see Appendix D for the feedback form).

Results

Objective 1: Materials and manufacturing

Identifying an appropriate material was accomplished by completing the design matrix (see Appendix B in Supplemental Materials) described in the methodology. Corriboard, which is a form of corrugated plastic sheeting, was identified as the optimal material. The key properties that made corriboard the optimal material were that it was waterproof, lightweight, and rigid. Part of the initial shelter assessments involved determining how they manufactured their current shelters. The majority of potential users built their own shelters with simple hand tools. To allow users to manufacture, install, and maintain the origami shelters, we decided to build our origami shelter in the similar manner.

Objective 2: User-based design

In total, the team conducted interviews and assessments with four stakeholder sets: slum residents, urban homeless, street vendors, and one of the advisors for the IIT-Mandi trekking club. We used standard interview format with most stakeholders, and an unstructured interview for the trekking club advisor.

Figure 12 summarizes the shelter needs of the potential stakeholders and maps those needs to the benefits of an origami shelter. The street vendors, for example, reported not needing a shelter as they rent apartments for 2-3 months in each town they travel to, and thus were not included in the figure. As indicated in Figure 12, an origami shelter would most benefit those with a need for a semi-permanent or highly portable shelter.

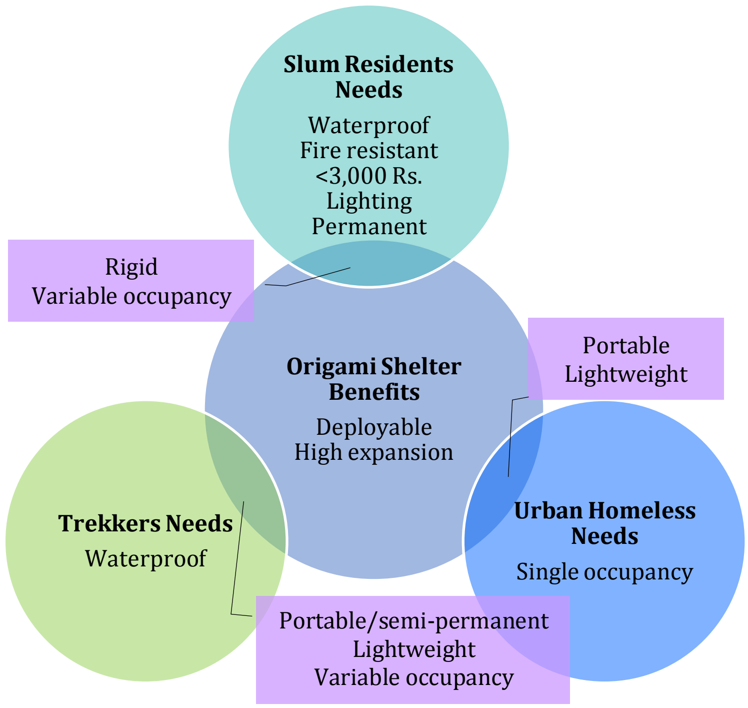

Figure 12: Mapping of the benefits of an origami shelter to the needs of each potential stakeholder group.

Although not all of the user groups proved to be well-suited to an origami shelter, they all provided valuable information on what could be potentially beneficial for a semi-permanent shelter. For example, Figure 13 shows the number of occupants per shelter, indicating that up to 6 people frequently reside in a relatively small shelter.

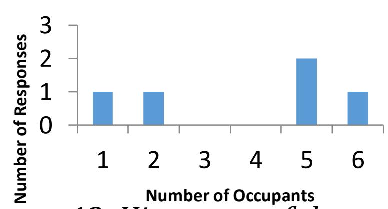

Figure 13: Histogram of the number of occupants per shelter

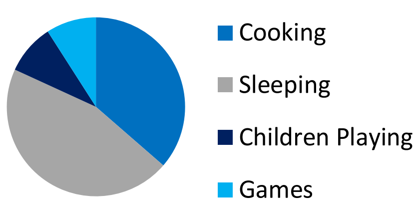

Figure 14: Popularity of activities conducted in the shelter

Figure 14 indicates that the two most popular activities performed in the shelter are cooking and sleeping. From this information, it was decided that the origami shelter must be large enough to accommodate multiple beds, an area for food preparation, and be fire resistant.

These findings indicated that semi-permanent shelters were the most appropriate match for origami structure applications. The target audience of a semi-permanent shelter includes, but is not limited to, trekking companies, roadside vendors, migratory construction workers, and special event organizers.

Objective 3: Produce 3 final products

We created computer aided design (CAD) models to explore different designs (see Figure 15). The model in Figure 15a was chosen as the best design for initial prototyping as

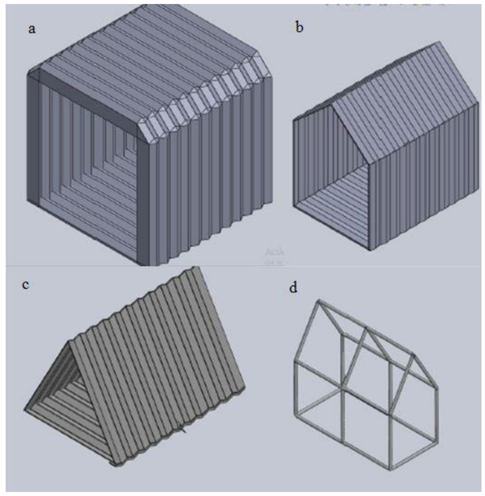

Figure 15: The isometric views of four of the initial shelter designs. (a) is a simple rectangle (b) is a simple pentagon (c) is an A-frame style shelter. (d) is an a pole-based alternative to an origami structure

it had the capability to be closed on both ends, had a large amount of usable interior space, and included only simple reverse folds and seam joints. Moving forward, the only change to that design was to make one of the sides shorter so that the roof slanted to allow for water drainage and prevent snow accumulation.

The CAD model was used to generate a mathematical model of the shelter design which took the material properties and basic shelter dimensions as inputs and calculated interior volume, dynamic heights, dynamic floor area, weight, dynamic length, percent elongation, and floor width based on the joint angle (see Figure 16).

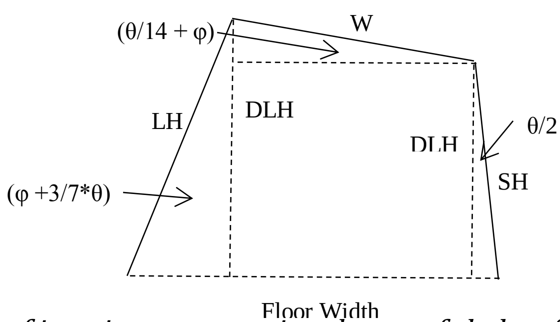

Figure 16: Sketch of interior cross-sectional area of shelter for mathematical model. LH is the long height, SH is the short height, and W is the width as measured on the flat panel before folding. θ is the joint angle, the angle between two panels and φ is the desired roof angle. DLH and DSH are the dynamic heights.

This model was used to optimize the shelter parameters so that the final shelter was adequately sized for an average person to stand in while maximizing usable interior space and minimizing both cost and weight. The model assumed that for every degree the joint angle increased, the roof angle decreased by 1/14 of a degree, the short side angle with the roof increased by ½ of a degree, and the long side angle with the roof increased by 3/7 of a degree. Ultimately, interior volume was chosen as the property to optimize and thus the parameters were adjusted to find the maximum interior volume while maintaining standing height on the longer of the two sides (see Figure 17). The maximum volume was achieved at an angle of 135˚ but this did not allow for standing height so the minimum acceptable volume, found at 45˚, was used to create the first prototype.

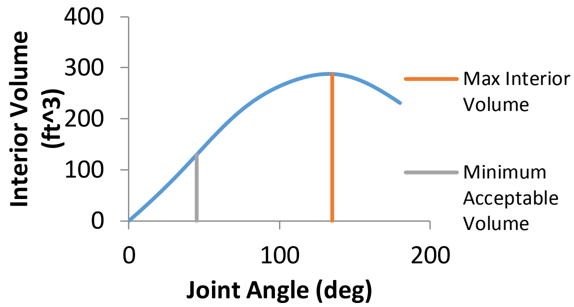

Figure 17: Interior volume graphed as a function of joint angle.

At the minimum acceptable interior volume, all model parameters were calculated to determine the dimensions and necessary angles for folding the corriboard sheets to create a full-scale model (see Table 1). These parameters were calculated for a model with 18 eight inch panels, LH=7', SH=5'5", w=3'3", thickness of 1/8", and a density of 4.68 kg/ft^3.

Table 1: Model parameters calculated when the minimum acceptable volume is achieved

Parameters at Minimum Acceptable Volume	
Joint Angle (deg)	45
Roof Angle (deg)	19
Interior Volume (ft^3)	130
Dynamic Long Height (ft)	5.5
Dynamic Short Height (ft)	5
Dynamic Length (ft)	4.6
Dynamic Floor Area (ft^2)	47
Weight (kg)	14
Weight/Area (kg/ft^2)	0.29
Elongation (%)	2449
Floor Width (ft)	9.5

An initial prototype was constructed out of six sheets of corriboard connected with both overlap and seam joints (see Figure 18). The seam joints were sealed with tarp and the overlap joints were connected with PVC cement and bolts. This prototype also included additional features that users identified as beneficial such as an integrated floor, windows, ventilation, and the ability to close on one side. While this prototype was the full height of the final design, it was 1/3 of the length of the final design as cost was an important consideration. This version was created for about 3,000 Rs.

Figure 18: An isometric view of the initial prototype (top), collapsed shelter (bottom)

The final prototype was constructed of 14 sheets of corriboard connected with both seam and overlap joints (see Figure 19). Hinges were added along the short side and roof to increase compactness. Additionally, it included 'smart' features such as an integrated floor, rain water collection, solar lighting, internal storages, and ventilation. This version expanded to nearly 20ft in length, 6ft in height, and 5ft in width. With all these additional features, this version was created at a cost of about 10,000 Rs.

Figure 19: Isometric view of final prototype (top), collapsed shelter (bottom)

Although the initial goal of this project was to create three final shelters, upon completion of the initial prototype and the first final shelter the team decided to reduce this number from three shelters to a single shelter. The primary reasons for this decision were based on the cost of producing additional shelters and the time it would take to manufacture them. Despite allowing for simultaneous field-testing, creating additional shelters would result in a diminished ability to perform extensive field-testing in the time allotted.

Objective 4: Field-testing

Experimental Design Validation

Laboratory testing was employed to verify material properties and shelter design requirements. This was used to verify fire resistance, fatigue resistance through both folding and creep, as well as water resistance. During the flame test cardboard was the only material to ignite; corriboard melted slightly in similar conditions, but only when exposed to direct flame. A foil and tape covering only marginally improved corriboard's fire resistance.

Fatigue resistance was tested for both folding and creep to ensure the shelter could withstand repeated deployment and extended use. Figure 20 shows the results of the folding fatigue test; the corriboard did not fail after 1000 folds and there was no indication of failure. The 1000 fold threshold was used to simulate a shelter life of 5 years with the shelter deployed for 2 month increments each year and a safety factor of about 20. The creep fatigue test was used to determine corriboard's behavior over time when loaded and to examine the effects of folding on creep resistance. The weighted mountain folded

Figure 20: Folding fatigue resistance results

piece performed nearly as well as the unweighted flat piece over an 8.5hr period; in all cases some creep was observed (see Figure 21).

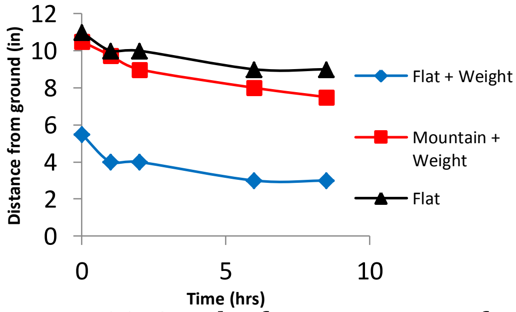

Figure 21: Graph of creep response for folded and unfolded corriboard

Water resistance was tested in two parts: testing of the shelter prototype and laboratory testing of the corriboard itself. During the prototype water testing, neither the overlap joint nor the windows leaked at all, the seam joint showed minimal leakage, and the shelter shed water efficiently (see Figure 22). The laboratory testing revealed that when exposed to water for 24 hours, the corriboard remained fully waterproof.

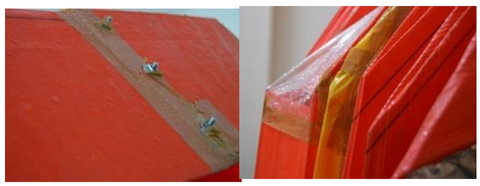

Figure 22: Water testing of shelter prototype. Water beading is visible

Qualitative field-testing

The shelter prototype was field-tested by ten volunteers: three construction workers and seven students. Three of the students participated in overnight field tests and the other four participated in the time trials described above. All volunteers were asked the same set of interview questions. Figure 22 shows all of the responses to the interview questions as fractions.

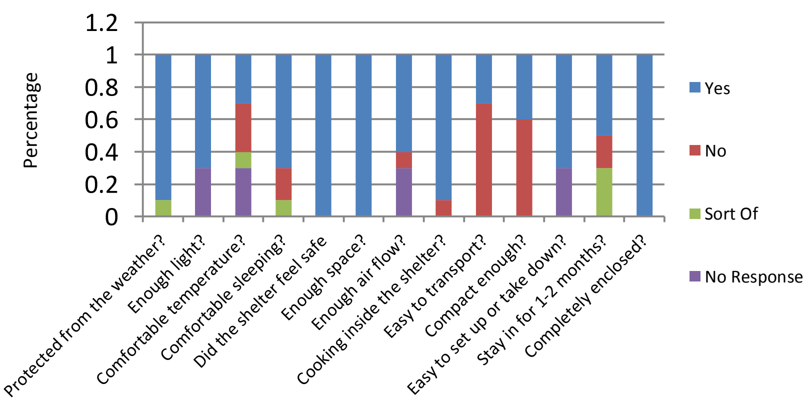

Figure 23: Field-testing feedback results for students and temporary construction workers

The temperature, compaction, and transportation questions show the most negative responses and the safety, space, and enclosure questions are the only questions with 100 percent agreement.

Once the final prototype was completed it too was field-tested with prospective users. The team met with and demonstrated the shelter to temporary construction workers, slum residents in Mandi, and roadside vendors (see Figure 24). The shelter was received with mixed positive

Figure 24: Meeting with slum residents during field-testing

feedback by the construction workers; 70% thought the shelter was innovative and potentially useful, while 30% thought the shelter need improvements in manufacturing to be useful. The primary areas of improvement involved making the shelter more wind and water resistance and improving the rigidity. All of the nearly 20 slum residents surveyed enthusiastically supported the shelter and felt its features completely met their needs. Specifically, they appreciated the deployability as during monsoon season they frequently need to move their shelter in order to avoid water accumulation. Although they do move their shelters, residents saw no need for the additional compaction, offered by the hinges. The roadside vendors thought the shelter was interesting but not well suited for their needs as they do not change locations and already have a compact setup. However, one of the vendors mentioned that some of the fruit vendors in Kullu do move between locations and thus the shelter may be useful in that scenario.

Discussion

The data revealed several considerations about the user set, the viability of an origami shelter for production, and the physical properties of an ideal structure. Overall, from the surveys, mathematical modelling of the shelter, and physical prototypes, it was clear that an origami shelter was best suited for stakeholders with a need for semi-permanent shelters. This user group included trekking companies, special event organizers, and temporary construction workers, among others. While the residents of the slums in Mandi are not ideally suited towards a semi-permanent, easily compactable shelter, with a few simple modifications, it would meet their needs and satisfy all of their needs. Traveling vendors and their families tend to rent apartments in each city, and required housing beyond the capacity of a shelter. Urban homeless users required a single personal structure that could be set up on the side of the road; although origami shelters are portable and can easily compact, on a small-scale they are heavier and less compact than tents and thus are not the best solution for this user group. From the interview with the trekking club advisor, it was clear that for an individual trekker, a tent was the best solution; however, he pointed out that many guide companies create semi-permanent base camps for their clients and this could be good market for origami shelters. Finally, although an origami shelter was best suited for semi-permanent use it can also have applications for users that need highly portable shelters.

In terms of the physical product, the initial full-scale prototype provided valuable feedback on manufacturing specifications and usage. While origami can produce simple and streamlined structures on a small-scale, the manufacturing limitations of full-scale structures reduce some of the benefits origami provides. For example, raw materials, including corriboard, come in specific sizes that are not large enough to create an entire structure from a single sheet; therefore joints are required which reduce the rigidity of the structure. Additionally, it is difficult to fold thicker materials such as corriboard, which makes it challenging to create accurate full-scale structures. To address some of these issues future versions should have accurate construction protocol, including jigs or fixtures for folding, less obtrusive attachments at the overlap joint, replace all seam joints with overlap joints, and any cutting or drilling should occur prior to folding. Additionally, the final prototype included hinges to aid in compaction but these proved to significantly degrade the rigidity of the structure and thus should be avoided in future versions.

The initial field-testing allowed the team to create a prioritized list of design changes for the final shelter by identifying the properties of an ideal shelter. Nearly all of the respondents indicated that the shelter was not compact enough and was difficult to transport, leading to several design changes in the final structure, which included folding the entire shelter into a single piece. Respondents also expressed displeasure with the initial floor setup of unattached tarp spread across the ground. To combat this, the team included a floor that firmly attached to the walls to provide full waterproofing. The temporary construction workers strongly desired a lock on the shelter and thus the final design has the ability to fully enclose and lock. The full list of design changes desired for the final shelter was as follows:

1. Better sealed and stronger joints
2. More compact when collapsed and easily transportable
3. Integrated floor
4. Full enclosure and lockable
5. Improved windows
6. Improved vertical height

The final design incorporated all of these features except for improved windows. Increased compaction was the only design change not to be received positively by either users or the designers. The final field-testing also revealed a list of new design changes for future versions:

1. Raised floor
2. Internal frame
3. Only use overlap joints and connect rigidly with metal strips or multiple bolts
4. Additional ventilation

These changes would reduce the shelters portability but greatly increase its rigidity and weather resistant and therefore make it more valuable for users with a need for semi-permanent shelters.

Project Outcomes

After 6 weeks of trial and feedback, the team completed a final full-scale origami shelter that met stakeholder design requirements and included a selection of 'smart' features. Additional deliverables included a manual documenting the assembly, compaction, and transport of the shelter as well as a list of features which can be added by stakeholders using built in mounts (see Appendix C, Supplemental Materials for this manual).

The base model origami shelter is about 6 feet tall, 5 feet wide, and 20 feet long, but is modular so both the length and width can easily be extended by adding more panels. It has the ability to fold down on both ends and lock to create a secure interior space. In addition to the water resistance, fire resistance, and rigidity provided by the material itself, the shelter comes with a standard selection of 'smart' features including: solar powered lighting and device charging, interior storage, ventilation, and a rainwater catchment system. Perhaps the single most important feature of this origami shelter is its extreme adaptability; only minor modifications to the base model are needed to customize the shelter for different users. For stakeholders such as the slum residents, who require a more permanent shelter, the width of the shelter can be extended by adding another panel, the hinge joints that aid in folding can be replaced by overlap joints to increase rigidity, extended vents can be incorporated, and detachable insulation can be added to the interior.

For stakeholders such as trekking companies, special events organizers, and vendors, the shelter can be expanded or contracted by adding or removing panels and increased storage can be added. For stakeholders such as farmers, who may want to use the origami shelter as a greenhouse instead of as a shelter, the color of the corriboard can be changed to transparent or white to allow maximum light transmittance. Furthermore, increased storage solutions and overhead hooks to hang pipes from can be added, and the rain water catchment system can be routed back into the shelter to provide water for the interior plants. Changes in dimensions and switching hinge joints to overlap joints can be done based on the need of the stakeholder. While these are only a small selection of adjustments that can be made, they highlight the full extent of the range of adaptations can be made to the shelter to meet the specific needs of various stakeholders.

Although this version of the origami shelter is highly adaptable we recommend that future iterations of this project consider non-origami style shelters as well. Non-origami shelters can provide a lighter and more compact structure than origami structures that is more targeted for users requiring a small and highly portable shelter. These style of shelters may be well suited to the needs of both the urban homeless and local herders.

Additionally, while this version of the shelter is a versatile improvement over the previous version and other existing shelters it requires improvements to be marketable. These changes are addressed in in detail in the discussion but overall the team feels that the improvements to the rigidity are the most important as this shelter is designed for longer term use.

Conclusion

The final shelter was designed to be waterproof, fire resistant, lightweight, affordable, as well as include some 'smart' features such as solar power. The shelter produced met these requirements as confirmed by both laboratory and field-testing. The use of corriboard is an innovative feature that is not found in currently available origami shelters and provides the structure with the key benefits of being waterproof, fire resistant, and lightweight. For the area and volume achieved, this shelter is lighter than both the current shelters of temporary construction workers and the previous iteration of this project. Additionally, this shelter is modular and can be fully enclosed and locked which are features not found in many available shelters. The inclusion of 'smart' features such as solar power, water catchment, storage, and lighting make this shelter an improvement over available semi-permanent shelters in terms of extended use and quality of life. Overall, we have shown that origami can be used to create high-quality shelters for semi-permanent use and, while not ideal, it can additionally be used for small-sized temporary shelters or for permanent shelters.

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Supplemental Materials

Appendix A: Summary of Potential Materials

Table 1: Potential materials with advantages and disadvantages listed

Material	Advantages	Disadvantages
Cardboard (and derivatives)	• Locally available • Cheap • Easy to use • Lightweight	• Flammable • Not water resistant
Aluminum	• Waterproof • Recyclable • Rigid • Flame resistant	• Expensive • Heavy
Canvas (cotton)	• Compactable • Locally available • Water resistant • Biodegradable	• Heavy • Flammable
Polypropylene	• Waterproof • Recyclable • Rigid	• Non-biodegradable • Not locally available
Nylon	• Lightweight • Water resistant (when treated) • Fire resistant	• Not rigid • Non-biodegradable
Tyvek	• Water resistant • Recyclable	• Flammable • Non-biodegradable • Not rigid
Tarpaulin (Polyethylene)	• Locally available • Water resistant	• Not rigid • Flammable
Kevlar	• Fire resistant • Durable • Water resistant	• Expensive • Not rigid
Wool	• Fire resistant • Water resistant • Locally available • Biodegradable	• Not rigid • Non-recyclable
Carbon fiber	• Water resistant • Fire resistant	• Expensive
PLA (Polylactic Acid)	• Fire retardant • Biodegradable • Recyclable • Water resistant	• Not rigid
ABS plastic	• Rigid • Water resistant • Recyclable	• Non-biodegradable • Flammable
Polycarbonate	• Rigid • Waterproof • Fire resistant	• Non-biodegradable • Non-recyclable
Nomex (Aramid polymers)	• Fire resistant • Water resistant	• Not rigid • Non-biodegradable • Non-recyclable
PBI (Polybenzimidazole)	• Fire resistant • Water resistant	• Not rigid • Non-biodegradable • Non-recyclable
Teflon	• Waterproof • Fire resistant • Recyclable	• Not rigid • Non-biodegradable

Appendix B: Design matrix and appropriate ranges for metrics

Table 2: Breakdown of metric ranges for each property

Property	**Fire Resistance**	**Water Resistance**	**Cost**	**Weight**	**Rigidity**	**Compactness**	**Biodegradability**
Metric	Melting Point/Ignition Temperature	Water Absorption	USD	Kg/m^3	Y/N	Rating	Y/N
1-Range	<300C	>10%	>15	>1.6	N	No fold	N
2-Range	300-500C	5-10%	7-15	0.16-1.6	--	Some fold	--
3-Range	>500C	<5%	<7	<0.16	Y	Easily fold	Y

Table 3: Material properties design matrix

Property	Cardboard	Nylon	Tarp	Polypropylene (Corriboard)	Canvas (cotton)	Tyvek	Aluminum	Wool	Kevlar
Fire Resistance	2	2	2	2	1	1	3	1	3
Water Resistance	1	2	3	3	1	3	3	2	2
Cost	2	2	3	3	3	3	1	3	1
Weight	2	2	1	2	1	1	1	1	2
Rigidity	3	1	1	3	1	3	3	1	3
Biodegradability	3	3	1	1	3	1	1	3	1
Raw Total Points	13	12	11	**14**	10	12	12	11	12
Portable Shelter Score	21	22	24	**28**	19	25	21	22	20
Permanent Shelter Score	22	21	22	**27**	15	23	**27**	18	25

Appendix C: Current shelter feedback form

Current Shelter Feedback Form	
Interview Logistics	
Interviewer(s):	
Date:	**Start Time:**
Location:	**End Time:**
Basic Interviewee Demographics	
Interviewee(s):	**Interviewee Age:**
Interviewee Profession:	
Interviewee Gender:	
Questions	
Social Dimension/User Experience Questions	**Response**
How many people live in your shelter?	
What kind of activities do you do inside the shelter (cooking, games, etc.)?	
Where do you sleep?	
Do you store belongings anywhere inside the shelter?	
How do you carry things when travelling?	
What do you typically carry when travelling?	
Do you remake your shelter every time you move?	
How did you make/repair your shelter?	

How often does your shelter require repairs?	
What is your average income?	
Technical Specifications Questions	
Number of entrances	
Completely enclosed or open ended	
Does the shelter have the potential for modularity?	
Does the shelter include multiple layers?	
Is the shelter freestanding?	
What kind of lighting is used?	
How is the shelter heated?	
Covered area per person	
Height of shelter	
Weight (rough estimate)	
General Comments:	

Appendix D: Field-test feedback form

Field-Testing Feedback Form	
Logistics	
Interviewer(s):	**Form ID:**
Date:	**Prototype #:**
Location:	**Start Time:**
	End Time:
Interviewee Demographics	
Interviewee(s):	**Interviewee Age:**
Interviewee Profession:	**Interviewee Gender:**
Questions	
Did you feel protected from the weather?	
Did you have enough light?	
Was the temperature comfortable?	
Were you able to sleep comfortably?	
Did the shelter feel safe (physically and psychologically)?	
Was there enough storage space?	
Was there enough air flow?	
Would you feel comfortable cooking inside the shelter?	
Did having this shelter make you feel uncomfortable or isolated from the rest of the group?	

Was this easier or harder to transport than your previous shelter?	
How easy was it to set up and take down the shelter?	
General Comments:	

Appendix E: Design, Fabrication, and Usage Manual

Smart Origami Shelters

User Manual

Indian Institute of Technology and Worcester Polytechnic Institute

Indian Institute of Technology Mandi

WPI

Project Background

Who Are We?

A team of IIT and WPI students worked collaboratively to develop a new type of shelter influenced by integrated smart technologies and origami-style construction methods.

What is an Origami Shelter?

An extremely versatile shelter made of rigid panels that remains lightweight and easily deployable. Readily available for both temporary and permanent use; including trekking, green houses, special events, and much more!

Design Summary

Shelter Features

The base model origami shelter is about 6 feet tall, 5 feet wide, and 20 feet long. It has the ability to fold down on both ends and lock to create a secure interior space. The shelter comes with a selection of smart features including: a rainwater harvesting, interior storage, ventilation, and mounts for solar panels. This origami shelter is also extremely adaptable; only minor modifications to the base model are needed to customize the shelter.

Weather Resistance

To be able to target multiple user groups for both temporary and permanent use, this shelter was designed to be able to withstand changing weather conditions. Made of corriboard sheets, the shelter is inherently waterproof and has rigid walls. To allow for an easily maintainable interior environment, ventilation is also available on select wall panels and can be opened at the discretion of the user. Lastly, rainwater collection spouts utilize the existing roof slope to allow for a self-sustainable living environment.

Livable Space

For permanent use, it's important for the user to have an open interior space that is easily adaptable to their needs. Therefore, the design incorporates a locking mechanism, multiple built-in storage options, and a fire resistant structure to allow for cooking within the shelter.

Customizable

To maintain the flexibility which origami allows, this shelter was designed to allow the user full customization. The structure can be compacted and expanded to different points of linear elongation, and to create three basic forms. These include having both ends open, one end open, and both ends closed. This shelter was also designed to be modular, so that the total length can be adjusted to meet the user's needs. Many of the smart features available can also be modified as needed, including the

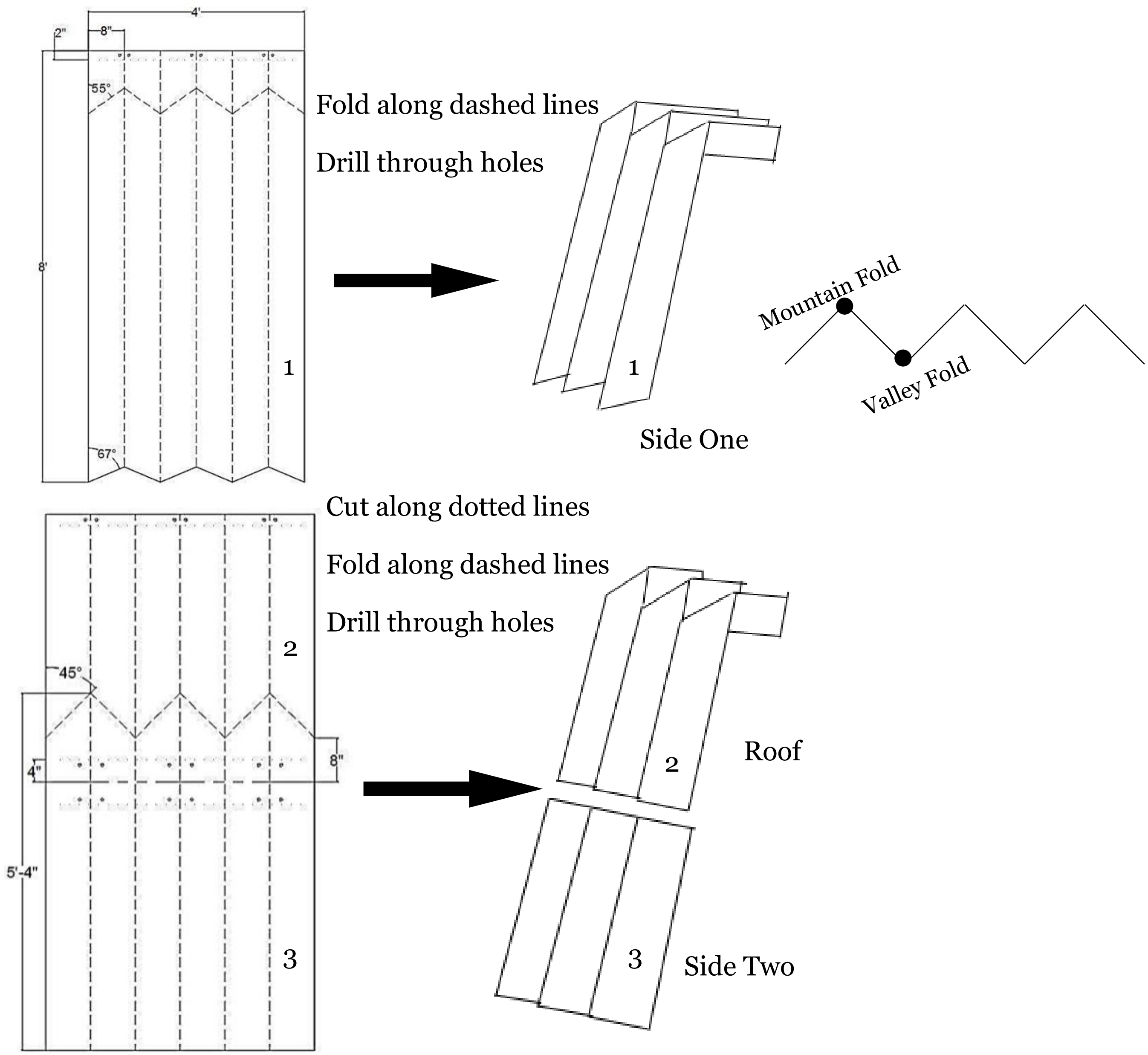
1: Shelter open at both ends. 2: Shelter with one end open. 3: Shelter closed at both ends.

internal storage options, rainwater collection and the use of solar panels.

Assembly Instructions

Along with being highly customizable, this shelter was designed to utilize simple construction methods and commonly available tools. Note that the base shelter model has seven arches.

Origami Folds



Reverse the folds along the dashed lines, and accordion fold the panels so that *1* and *3* begin with a mountain fold, and *2* begins with a valley fold. Repeat for each arch.

Hinge Joints

Bolt the three arch components together so that there is a two inch overlap. To prevent water from leaking into the shelter, attach panel *2* above panels *1* and *3* at each overlap. Add pins as needed to the connection between *3* and *2* to increase stability. Estimated need is two pins per arch. Cut off corners at each hinge joint to allow for freedom of movement. Repeat for each arch.

Seam Joints

Connect each arch using strips of tarp stitched to the corriboard. Leave a gap of 1/4” between the arches.

User Guide

This section is divided into three parts. User Customization provides brief descriptions of the ways in which the user may manipulate the basic shelter to fit their needs. Included Features details the smart features which come with the basic shelter, and Optional Features explains the possible additions and alterations which can be made by the user.

User Customization

Along with ease of deployment and transportation, this shelter was designed to be readily customizable by the user so that it can meet the needs pop varying groups of stakeholders. Without altering the basic structure, the user can easily manipulate the shelter through expansion control, the addition or subtraction of modules, and the rearrangement of the integrated floor.

Expansion Control

Though the use of interior tension ropes and staked lines, the user is able to control the linear expansion and form of the shelter. The shelter is capable of 2000% linear elongation from its fully compacted state. As the shelter expands, both vertical height and floor area change in relation to the adjustments. This shelter can also take on three basic forms. It can be expanded with both sides open, one side closed, and both sides closed.

Modularity

This shelter was constructed out of multiple arches of corriboard attached with seam joints. Through the addition or subtraction of these modules, the shelter's overall length can be easily adjusted to fit the needs of the user.

Integrated Floor

The shelter's final fully customizable feature is the ability of the integrated floor to adjust to any of the shelter's configurations. Made out of tarp, it attaches with velcro to the sides of the shelter. As the shelter is manipulated, the floor requires only minor adjustments to match the required dimensions. With one or both sides open, the integrated floor can also be used as a temporary cover for the doorway(s).

Included Features

In addition to the shelter's ability to be readily customized, it has built-in smart features designed to fully utilize inherent qualities of the chosen folding pattern. These features include the shelter's ability to be locked from both the exterior and interior, ventilation, interior storage systems, and rainwater collection.

Lockable

This shelter includes the ability to lock the completely enclosed shelter, from both the inside and outside, so that possessions may be safely stored. Each end of the shelter has a hole at the top of the arch. When closed, these points may be securely locked to a stake which is located within the doorway.

Ventilation

To maintain a comfortable living space, this shelter includes open ventilation on select panels. These vents may be opened and closed at the discretion of the user. When closed, these vents can withstand inclement weather.

Interior Storage

This shelter includes multiple built-in storage options, including hooks on the ceiling for hanging lights and other equipment, pouches on the interior for small objects, and shelves within select folds that deploy with the shelter.

Rainwater Collection

To allow for self-sustaining living conditions, this shelter includes a rainwater harvesting system that deploy with the shelter. The standard shelter has built-in spouts along the roof, while piping and storage can be added at the user's discretion.

Optional Features

On top of the shelter's built-in smart features, the design further incorporates flexibility by allowing for the inclusion of solar panels and full-shelter repurposing as required by the user.

Solar Power Compatible

Includes mounts on roof which are adjustable to varying sizes of solar panels. Wiring threads through roof or side hinge joints to attach to interior mounted lights and/or charging ports. Solar panel and lights are not provided.

Adjustable Materials and Further Customization

For users who require a more permanent shelter, the width of the shelter can be extended by adding another sheet of corriboard to the roof or sides of each arch, the hinge joints that aid in folding can be replaced by overlap joints to increase rigidity, extended vents can be incorporated, and detachable insulation can be added to the interior. For users who may want to use the origami shelter as a greenhouse instead of as a shelter, the color of the corriboard can be changed to transparent or white to allow maximum light transmittance. Furthermore, increased storage solutions and overhead hooks to hang pipes from can be added, and the rain water catchment system can be routed back into the shelter to provide water for the interior plants. Changes in dimensions and switching hinge joints for overlap joints can be done based on the need of the stakeholder. While these are only a small selection of adjustments that can be made, they highlight the full extent of the range of adaptations can be made to the

1: Locking system. 2: Interior pocket for storing small objects. 3: Integrated floor. 4: Ventilation panel. 5: Rainwater catchment system.

shelter to meet the specific needs of various stakeholders.

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Appendix F: Supplemental images

Figure 25: Assessing current shelters

Figure 26: Current shelters of construction workers

Figure 27: Storm testing the first prototype

Figure 28: Discussing final shelter with slum residents

Figure 29: Fully closed shelter

Figure 30: Partially closed shelter

Figure 31: Meeting with Mandi residents about the final shelter