Temporary Shelter for Refugees
by
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Merit

"I hereby declare that, except where specifically indicated, the work submitted herein is my own original work."

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Temporary Shelter for Refugees - Technical Abstract

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Temporary Shelters are not temporary; they are permanent until the next one comes along. The shelters provide protection from the elements, warmth, security and a home for displaced populations. Currently refugee tents are not meeting the transitionary needs of disaster hit people: the tents rip easily, last only a few months and are useless once broken. This project aimed to improve the design of transitionary tent frames, such that they are easier to repair, adapt and incorporate into more permanent structures.

The project was undertaken in collaboration with ShelterCentre, a humanitarian agency supporting the transitional shelter and settlement of displaced peoples affected by conflict or natural disaster. The aim of the project was to optimise the design of the tent frame in line with ShelterCentre's criteria, specifically to have angle sections as the main member type, and to produce a tent frame that was buildable, repairable, upgrade-able and within weight and cost limits.

As there was little literature available on the subject, trips were undertaken to gather information. The first was to see the tents currently available at an Oxfam shelter event. The ShelterMeeting conference was attended and feedback received on the initial project work, as well as advice obtained on how best to improve it. During the Christmas vacation two weeks of research was done in the refugee camps of the earthquake struck NWFP region of Pakistan. All the data gathered was invaluable to understanding the background and context of the project, as well contributing towards the more technical aspects of repairability, constructabililty and the loading scenario.

Aluminium was the material chosen for the angles as it alone of the commonly available engineering material met the cost, weight and corrosion criteria. The loading scenario applied was from internationally agreed standards: a 75 km/hr wind load laterally and one foot of snow vertically.

The joints were the critical areas in the frame. The initial proposal of one bent gusset plate to support the joint was quickly found to be inadequate by a Lower Bound analysis. A second design involving two flat plates was then pursued. Four physical models and two CAD ones were made to further understand the geometries and construction issues. After initial plasticity estimates were done, a computer analysis was brought in to investigate elastic performance. Hand calculations were carried out to check the validity of the results obtained. As angles are doubly asymmetric their deflection is a complicated phenomenon and understanding this was non-trivial. It was found that the frame would deflect too much with this design, and any other lightweight unbraced design as the moments generated were too large. Therefore the decision was made to try a braced design.

The braced design incorporated cables to give a truss action to the structure. A number of design options were explored before one was found that met the social and construction requirements. The designs were evaluated by the same computer analysis package, and similarly checked by hand calculation. The final design had reduced moments and deflections by an order of magnitude and also allowed for a smaller, lighter cross section to be chosen, when compared to the unbraced values.

A quarter scale model of the final design was constructed and tested. When the results were compared with those predicted by the computer model it was found that there were come discrepancies between them but that these could be explained by various errors in both. It was concluded that the computer model was conservative but that further experiments would be needed before complete confidence could be had in the design.

The end result of the project is a design that is both lightweight and inexpensive, can be readily procured and repaired in the field, and is sufficiently simple that it can be quickly constructed, but sufficiently strong and stiff that it performs satisfactorily under the given loads. However there are aspects which need to be investigated further before the design can be mass-produced, namely the response to dynamic wind loading, the interaction with the tent covering and the exact nature of the support conditions.

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1. INTRODUCTION

Shelter is one of the main emergency needs of refugees; it provides warmth, security and protection from the elements to peoples who have just experienced a disaster. Every year there are disasters – both natural and political – that drive people from their homes and force them into refuge, recent examples are the Kashmiri Earthquake, the South East Asian Tsunami and the genocide in Darfur. In the emergency period directly after the disaster, any shelter will suffice, but as time progresses there is a need for 'transitionary' shelters which are robust, adaptable, and can last the months or (more usually) years before a family is re-housed. Ideally these shelters could also be integrated into any permanent home the occupants build, or at least be easy to 'upgrade', i.e. are able to incorporate corrugated iron sheeting roofs or brick walls, should materials become available.

1.1 Project Aims

The project aims to design an optimum tent frame that:

- Is composed of simple, commonly found sections (namely angles)
- Uses a minimum of different component types
- Is easy to construct, repair and upgrade in the field
- Is capable of meeting the brief from ShelterCentre, including loading, cost, weight, storage and social requirements

1.2 Background

The transitionary tents currently provided by the aid agencies often prove woefully inadequate for climates in the developing world, being frequently overturned in high winds, overwhelmed by snowfall and prone to leaking. The latter is a regular occurrence, and once the interior of the tent is damp, it becomes miserable to live in, susceptible to disease and difficult to store food in. The water gains access through rips and tears in the canvas. These mainly initiate at the joints, where the canvas is being pulled in different directions, and where the support pole wears through the fabric, especially when wind buffeting occurs. As the tents are usually tension structures, the prestress in the fabric causes the tear to propagate and let water in. The canvas (or more usually plastic sheeting) used weakens with time and UV exposure, further compounding the problem as the tent quite literally pulls itself apart. This happens within 4-6 months even in ideal conditions, and even sooner in a crowded refugee camp, resulting in a near constant demand for replacement tents.

If the tent is not a tension structure, but rather frame-supported, then many of the above issues can be negated; the canvas lasts longer and retains its water resistivity, making for a more pleasant living condition, while the structural integrity of the tent no longer decays markedly with time and so the tent can fulfil its objectives in providing protection from the elements. The obvious disadvantage to a frame tent is that the members need to be more massive to take the force that was previously carried in the canvas. This leads to extra weight and hence cost. Also more members are needed to fill the load paths previously through the canvas, and the joints between members are no longer straightforward. This adds further weight and introduces bolts (usually unnecessary in tensioned tents) which can become loose or lost.

The designs of the tents are often such that their erection is not intuitive, further reducing their performance as they are incorrectly pitched. Also there are a large number of social and cultural issues attached to housing that must be considered during design, otherwise the inhabitants will make their own changes as they see fit, and usually to the detriment of the structural capacity.

In addition to these faults, the tent frames are not easily repairable, as nearly all are made from steel Circular Hollow Sections, which cannot be readily replaced or mended with local facilities. Hence when a tent is deemed un-useable, its frame is either discarded or used as fencing, a clear waste of materials and workmanship that have been transported in at considerable cost and effort. The aim of using angle sections in this project derives from this issue – angle sections are available in nearly all developing world markets, giving more choice to aid agencies during procurement as well as giving refugees the chance of repairing if necessary. Also angles are packed easily to minimise volumes and can be used more readily in construction of more permanent structures.

The current market prices range from $250 for a very basic canvas design through to $2,000 for an army standard winterised tent. To be attractive economically to an aid agency, a tent must cost no more than $400. On the practical side, tent frames must weigh no more than 50kg (due to economies of airlifting) and need to be sufficiently simple to erect that a group of 5/6 can do so in half an hour. These conditions are the most constraining as a simple design typically requires heavier members whilst a light one is more complex and nearly impossible for traumatised persons to erect.

ShelterCentre is an NGO that focuses on refugee housing, particularly that in the transitionary phase. It holds biannual meetings with all the main aid agencies and donors with the aim of reaching a consensus on standards and strategy for shelters, as well as conducting research into an improved transitional shelter design. This project is one in a series done in recent years in conjunction with ShelterCentre. The overall ShelterCentre concept is for a modular portal frame tent that can be adaptable to most scenarios, and can be readily incorporated into a more permanent structure. The dimensions of this tent (see Figure 1) are fixed as regards this project, but there was freedom to innovate regarding the joint system and supports. Beginning with the idea of a frame that can be easily repaired and sourced in a disaster region, ShelterCentre came up with the original concept of a joint made only from angle sections and flat plate which formed the starting point for the project.

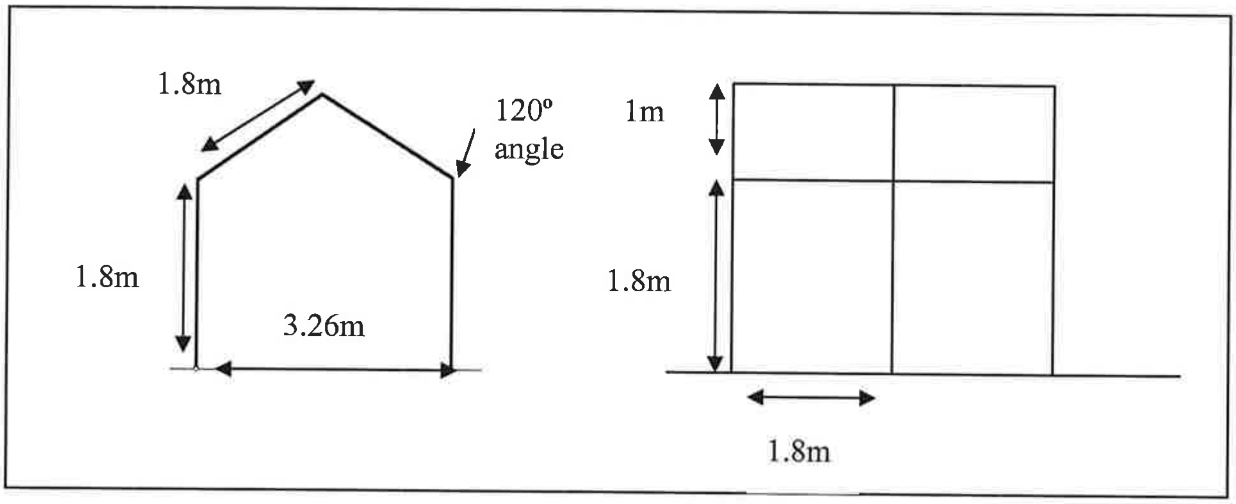


Figure 1: Tent Dimensions

Dr. Tom Corsellis, formerly of the Cambridge University Architecture Department, is a co-founder of ShelterCentre and had key inputs into the project. In particular, all major design changes were discussed with him so that they fitted in with the wider goals of the ShelterCentre mission, both technical and social, and to ensure the end product was practical 'on the ground'. This was an extremely useful opinion to have, complicated only by the fact that as ShelterCentre relocated to Geneva mid 2006, Dr. Corsellis was only occasionally in Cambridge, and the complexity of the concepts and arguments was such that face-to-face meetings were necessary to make design decisions.

1.3 Oxfam Conference : (30th June 2006)

At the very outset of the project ShelterCentre suggested a trip be undertaken to Oxfam Headquarters in Oxford to attend a conference on transitionary shelter that was being held there. The main attraction was that about 10-15 different types of transitionary shelter would be erected outside the event and it would be an ideal time to get an idea of what shelters were available, as well as having their advantages and disadvantages explained. It was useful to see these tents, as there were ones from each type of design, and from most major tent-distributing agencies. Also of benefit was the task of dismantling the tents at the end of the day, which gave a real insight into how each one worked and why some were not widely used as they were too complex.

1.4 Geneva Conference : (16th – 17th November, 2006)

The findings of the project at the time were brought to the second 2006 ShelterMeeting Conference in Geneva. This is a biannual gathering of the major aid donors, non-governmental organisations and other interested parties, with the aim of discussing, coordinating and agreeing initiatives, policy, good practice and technical specifications relating to the transitional settlement and reconstruction needs of populations affected by conflict and natural disasters [1].

The computer renderings of the two-plate joint were included in the ShelterCentre presentation on the first day, and the prototype passed around to garner the delegates' opinions. The response was positive – the idea struck most as an improvement - and advice on how to progress & what to keep in mind was useful as it was grounded in practical experience.

At the conference, ShelterCentre had set up their prototype tent with the 120° gusset plate, as shown in Figure 2 below. This was the original concept for the tent but it had already been ruled out as too flexible. Nevertheless it was useful to see the size and dimensions of the full tent, and how the canvas was incorporated into the design. It was also interesting to see how the tent was dismantled, and the problems involved - even with a group of six student volunteers it took forty minutes.

The presentations during the conference were not all directly relevant to the project but did give more context and background to it. There are many facets to the problem of housing refugees – from environmental to social to logistical – and ignoring various aspects has lead to long term issues that cannot be easily solved.

Possibly the biggest resource at the conference was not the formal presentations but rather the informal chats with participants outside the lecture theatre. Most had an opinion on what was vitally important in shelter design, and had experience to back up this opinion. Some imparted some useful suggestions on bracing, local workshops and the logistics of distributing tents. Also present were students who had worked on the tent design over the summer, who were well versed in the reasons for each feature, and the problems the project was trying to solve. They gave an extremely useful history of the tent design and what to watch out for when pressing ahead with changes.

Figure 2: Prototype Tent

1.5 Pakistan Trip : (3^{rd} – 17^{th} December, 2006)

As there was little background literature available on the subject it was necessary to make a visit to gather data first hand, discover the reality of the current tents and ask the refugees themselves what it is they most require in a shelter.

For this a suitable location had to be found – one that was safe (no conflict), relatively recent disaster (not so recent that tents all new, not so distant that tents no longer there) and preferably one with an international presence. The Kashmir region of Pakistan met all these requirements, and there was another CUED student heading out there, who had been there the previous summer and had contacts within, and knowledge of, the area.

1.5.1 Background

In October 2005 there was an earthquake in northern Pakistan, in the Kashmir region (see Figure 3). Over 70,000 people were killed and nearly 2 million displaced. A year on, most had been rehoused but 40,000 still lived in tents, and faced into another winter in cramped, damp conditions. These could be loosely divided into two categories: flood refugees and earthquake refugees. The flood evacuees had their homes partially destroyed by the earthquake, but could still live in their hometowns in makeshift shelters around their property. Because the rivers were blocked by landslides that occurred during and after the 'quake, flash floods occurred during the summer (due to melt water and monsoon rainfall) which washed nearly everything in their paths away. The earthquake evacuees had their houses destroyed in the 'quake and had been living in camps for 14 months, being periodically shifted as the government closes and opens camps. They often did not have their own land to move back onto, and without livelihoods they could not afford the increased land prices that were being sought. The government did not have a clear strategy for dealing with these people, hence there was a feeling within the camps that they are being forgotten and left aside in ripped tents.

Figure 3: Map of Pakistan Earthquake Region Highlighted

1.5.2 Trip Itinerary

During the Christmas Vacation a trip was made to the Mansehra, North West Frontier Province (NWFP) to conduct research on the tents in camps and villages around it. Dimensions of each tent type and its components were taken, and the inhabitants interviewed to understand as much as possible the problems with the tent frame.

Figure 4: Map of Mansehra Region

Concern is an Irish NGO involved with the rebuilding effort in NWFP but also was in Pakistan before the disaster and intends to stay on for development work, its main remit. It had a field office in Mansehra and worked with many local NGOs to meet the needs of the affectees in the medium-to-long term. Prior to the trip contact had been made with Dorothy Blane, the Pakistan Director of Concern, who is an acquaintance of Dr. Heather Cruickshank (a CUED lecturer and the project's Michaelmas supervisor) and had received the promise of support from Concern wherever possible.

On arrival in Islamabad, Concern kindly offered lodgings and support at their Mansehra Field Office for the duration of the trip. Shakaib Admed Khan was the Mansehra office manager and it was he who obtained permission to visit the various camps and projects. Kazim Amir was the logistics officer who then arranged transport to and from the sites – this was by land cruiser and with a local driver to navigate the narrow, congested mountain roads - and translators. With their help the following sites were visited:

1.5.2.1 Jabba Camp

The camp had over 600 families, or nearly 4,000 people, mainly flood evacuees, but about 500 were from the 'quake. This was the only government-approved camp in the region, opened in August 2006 and took in people who were evicted from other government camps closed when the disaster was declared officially over during the summer. As the weather was becoming colder, dozens of families were arriving down from the mountains each day during December.

There was a wide variety of tents present on the site:

Figure 5: TRCS Tent

The 500 earthquake refugees lived in robust Turkish 'lighthouses', as they are termed. These are dome tents supplied by the Turkish Red Crescent Society (TRCS) which are extremely warm and well built – plastic sheeting is riveted to an aluminium frame. Along with the US Army tents (predictably robust and made to a high specification), these were the most waterproof and were sturdy in high wind, making them by far the most sought after shelters on site, although they were among the smallest.

Figure 6: ILAP Tent

The rest of the camp population was sheltered in ILAP (International League Against Poverty) or IFRC (International Federation of the Red Cross) tents made from steel tubes and canvas. These are tension structures that leak profusely after a month, as once a tear forms it rapidly grows and is difficult to repair. The poles poke through the canvas to support it, a ready made water entry site, and the sides of the tent are poorly supported and face considerable wind load, hence rip extensively. The influx of water and constant damp made the interiors unhygienic, unsuitable for food storage and unbearable to live in after only 2-3 months.

The ILAP tents faired slightly better as they have 50mm diameter poles over 2m in length, hence could be dug in slightly without affecting headroom. The IFRC tent poles were only 20mm in diameter and could not be dug in without a very low ceiling, hence these tents blew over frequently, making them the least habitable on site.

The site was well run, with a primary and secondary school, a child protection officer and adequate cooking and sanitary facilities. The army provided security, as well as carpentry facilities so that wooden frames could be constructed over the worst tents. The camp manager seemed very knowledgeable and efficient, and maintained stores of discarded tents so they could be recycled. These were not frequently used as if a frame did bend or break, it was not replaced or mended, but rather a new tent issued; hence this store was full of ripped canvas and rusting tent poles, which would not be used as each tent type had a unique tube diameter.

1.5.2.2 Balakot

This town used to be the centre of tourism for the region. As it was the 'quake's epicentre it was almost completely flattened. Its populace was decimated and is still living in makeshift shelters amongst the rubble. The government has decided to relocate the entire town 5km away, but no one seemed to be moving.

Figure 7: Tent pole as fence post

Most of the people were living in huts constructed from corrugated iron sheets, timber and canvas, usually with a dilapidated tent alongside as a storage area. Any tents were of the ILAP style and well over a year old, hence severely worn. All habitable tents had been extensively repaired. Even still they leaked profusely and blew over in storms, which broke some poles. These were replaced by wooden poles and the metal fragments left in piles. The hodgepodge shelters were somewhat better, but still miserable. Interestingly, none used spare iron poles as structural members; instead these were used as fence poles.

1.5.2.3 Mountain Villages around Balakot

Figure 8: Mountain Tent

These people lived in sturdy hoop tents (either from the TRCS or of a very similar design) with 20mm CHS. Often ropes were tied between bars to further increase the stiffness but even still the tents sometimes deformed under snow loads (up to 4 feet in the depths of winter). In the worst snow storms the inhabitants had to brush the roof every 2 hours or risk collapse.

Much construction was going on in the mountains – water schemes, some reinforced concrete buildings (worryingly with no engineer and a lack of steel ties). Interestingly the communities often constructed huts by adding wooden planks and corrugated iron sheeting to tent frames, with successful outcomes. This disregarding of traditional housing methods (houses with a thick flat wood-&-clay roof and thin stone columns) was not witnessed elsewhere.

Figure 9: Newly built house

1.5.2.4 Mansehra Market

In order to assess the availability of parts, a survey was conducted in the local marketplace. Mansehra is an average sized village (estimated population of 60,000) in this reasonably remote region. It escaped major damage in the 'quake, and hence was the centre for commerce in the region. The market was very much demand driven, with many small shops stocking a variety of wares. Of 30 hardware stores visited, all had bolts, 3 had angle sections and only one had plates, though about half had sheeting and CGI (corrugated iron sheeting) and said they could obtain plate if necessary. Bolts were available in many imperial sizes, angles only up to 40x40x3mm and sheeting only up to 3mm (though these were rare). The town's most advanced workshop had power tools for cutting plates and angles, though most workshops had drills to bore bolt holes. Despite a possibly lucrative market for it, only one shop repaired and recycled tent poles

1.5.2.5 Muzaffarabad

This is the capital of the disputed Azur Jammu & Kashmir (AJK) region, a neighbouring state to NWFP. It was badly damaged by the 'quake but due to the importance of the city it was quickly rebuilt. Many refugee camps were located in the valley around it, all run by the Norwegian Refugee Council (NRC) with the help of the IFRC.

At the NRC offices, a meeting was held with their technical adviser, Jonas Torjesen. As a structural engineer, he had recently redesigned their winterised house tent. He revealed the frame was not analysed in any detail, intuition telling what size should be acceptable (20 mm diameter CHS poles), and otherwise the local manufacturer's recommendations accepted. His redesign was mainly concerned with the canvas – getting the seams waterproofed and well placed.

Figure 10: IDB Tent

That afternoon a tour was taken of two NRC camps with Rizwan Khan, Jonas' assistant. The first was for flood affectees, and had entirely house tents from the Islamic Development Bank (IDB). These were half a year old and in good shape, being relatively sturdy and waterproof. The next camp was populated by conflict refugees, who have lived in tents since partition. These refugees would only live in robust dome or house tents. They prepared the ground by levelling it, compacting it and laying gravel to promote water flow. Furthermore they placed pieces of corrugated iron in the sides and hung blankets along the roof to make it more hospitable.

1.5.2.6 Islamabad & Rawalpindi

On returning to Islamabad, a meeting was arranged with Tom Bamford, an NRC manager with experience in tent procurement and transport. He outlined the costs involved: $300 - $400 raw cost, $10 per tent road transport & distribution, airlift cost $50 per tent, and explained the vast sums involved in replacing tents in NRC camps every 4-6 months. He also told of some problems with local manufacturers – poor workmanship and materials that could only be mitigated by tight contracts and extensive quality monitoring.

On the final day a tour was undertaken of the Islamabad markets in search of angles, plates and bolts. Though it took an inordinate amount of time to reach the desired shops (due to the local custom of never admitting they don't know but rather giving their best guess), they did contain an immense selection of all three items. A visit was also made to Rawalpindi, a neighbour city to the capital Islamabad, which was the main commercial centre of the region. This had been recommended by hardware shop owners everywhere as the place which had angles of any size desired, plates up to 6" (150mm) thick and both metric and imperial bolts. A brief search of the teeming building supplies market proved these tales true. There were also welders here who could fashion built up sections in a few hours at low cost and the factories there could produce components to any given specification, but ensuring they did so was often arduous. However engineering plastics could not be located anywhere.

1.5.3 Conclusions

Over 20 pages of notes and 350 photos were taken during the two weeks, which provided hard data to compare the project's design with. The trip gave invaluable cultural context, technical background and human reality to the project, and imparted an important insight into the end use of the work. The factors important on the ground were noted and the inputs from the aid workers and the refugees were invaluable. Lastly the visit showed that the tent problems are very real for thousands of people and need to be solved without delay.

2. THEORY

Optimising the design within the constraints was the bulk of the project. The design scheme was that shown in Figure 11 overleaf, with many iterations completed over the course of the year before arriving at the final model. Plasticity and the Lower Bound Theorem were initially used to get rough ideas of the section sizes required, then a computer programme was used to find the elastic response with analytical hand calculations being used to check the results. The main assumptions were that the legs of the tent were pinned, and that the canvas effectively transmitted all the force to the frame.

During the summer a visit was paid to ShelterCentre's summer office in Cambridge. The problem context and background along with the proposed solution was explained, as was this project's context in ShelterCentre's research and the progress on the tent so far. The main aim set for the project was to design a frame using angle sections, ideally identical, with few other components.

A literature review was conducted over the first week of the project. The university libraries and the internet were searched for useful information. Any relevant articles were more aimed towards prestressed lightweight structures, a direction the project would not take. As little previous research has been done in this area, it is not surprising this route had to be abandoned early on. As no other means of gathering the necessary data were obvious, the practicalities of a trip to a disaster area with tents was investigated, as were funding sources for such an excursion.

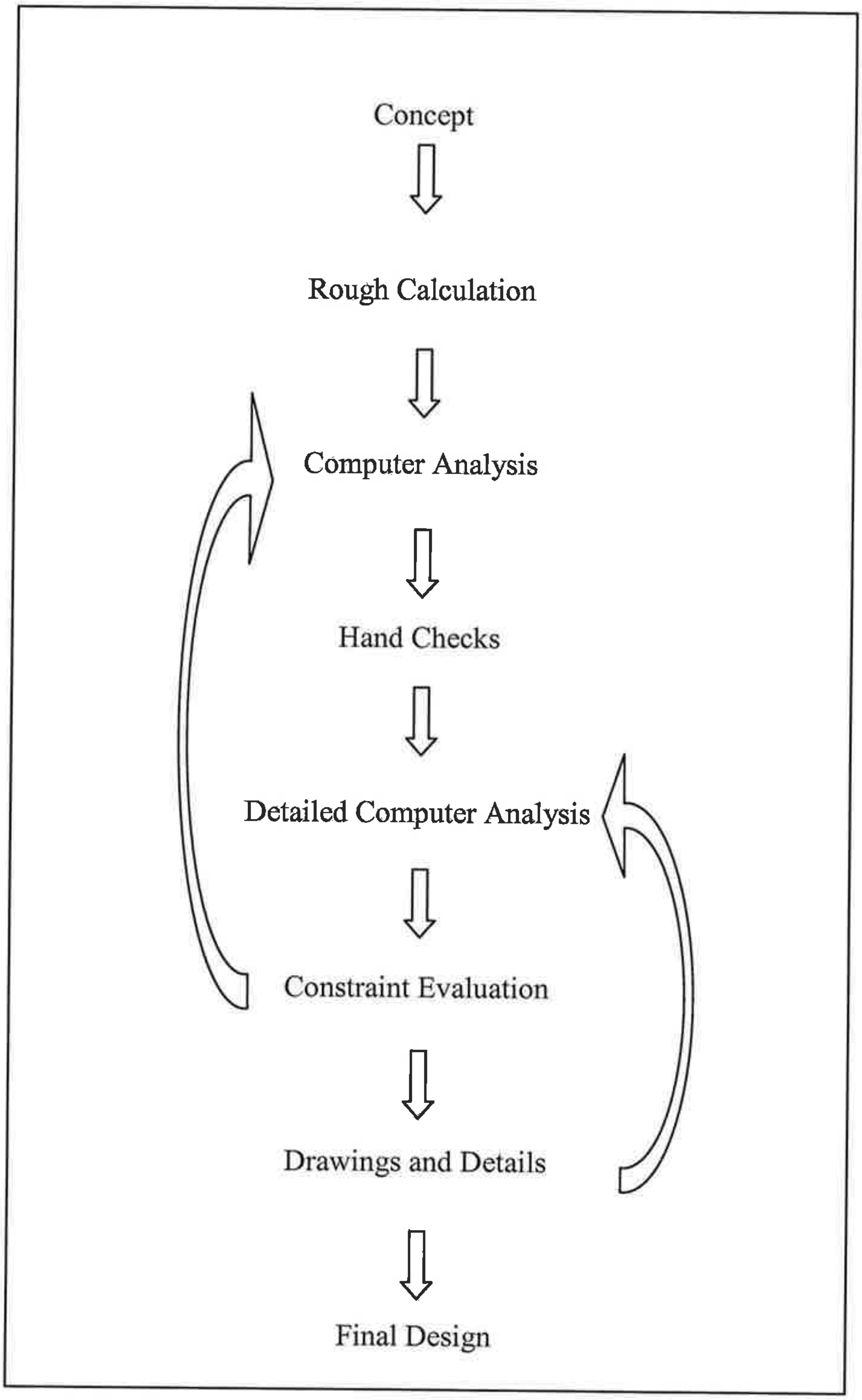


Figure 11: Design Process

2.1 Loading Scenario

The applied loads were taken from internationally agreed specifications for tents and transitionary shelters, supplied by ShelterCentre [2].

The lateral wind load is that of a strong gale, velocity 75 km/hr, which converts to a pressure of 0.3 kN/m^2 using Bernoulli's Equation. The vertical imposed load is the 300mm of dense snow, which becomes 0.3 kN/m^2 downwards on the roof. A Partial Safety Factor on loading of 1 is used for SLS calculations. At ULS, factors of 1.4 on wind load and 1.6 on snow load are used.

These loads do occur in disaster regions, such as the one visited. However there is some conservativeness built into them as tents are almost always pitched in sheltered areas and the inhabitants do not allow much snow to accumulate on them. Also the two peak loads are extremely unlikely to happen simultaneously. These redundancies in loading are included to allow for unforeseen loads or errors in construction.

For the very first design extra loading was considered: the weight of a light corrugated iron roofing sheet, estimated at 1.5 kN/m^2. After the first prototype was made it was decided this was overly conservative and there was no need to consider it further.

Dynamic loads were not considered as this would have broadened the project scope too much and been very complex. However it should be noted that these effects will be critical to the finished tent performance, especially buffeting causing fatigue failure.

The dead load was not included in initial calculations as the member mass was unknown. On completion of the final design checks were made including the dead weight, factored by 1.2 for ULS, and the structure was found to be satisfactory still. This is unsurprising as it is a lightweight structure.

One of the main assumptions of the loading is that the canvas transmits all the load to adjacent members. This requires a good binding system which was outside the scope of this project.

2.2 Unbraced Frame

The first half of the project focussed on optimising the joints of an unbraced frame. This was the design favoured by ShelterCentre, as it was simple, uncluttered and easy to construct. Eventually the benefits of bracing outweighed these advantages of the unbraced frame and the design was changed.

2.2.1 Single Plate Joint

The initial design supplied by the ShelterCentre involved only one gusset plate, bent at 120°, as shown in Figure 12. This had been devised over the summer to fit in nicely with the overall tent form. It was immediately suspected this did not have sufficient stiffness to maintain structural rigidity and calculations were undertaken to confirm or deny this. Moments at the joints were found via a rudimentary portal frame analysis, and with these the Lower Bound theorem was applied. As this was done, a full size tent was constructed by ShelterCentre. On completion of both, it was readily apparent that a stiffer joint arrangement was needed.

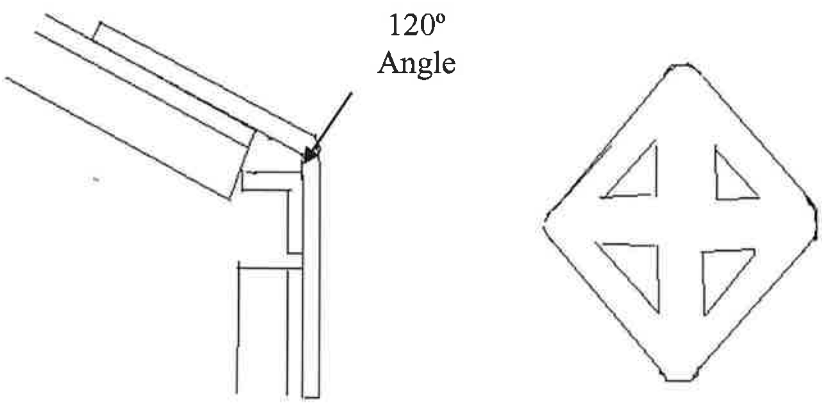


Figure 12: Elevation and Plan Views of 120° Plate Design

2.2.2 Two Plate Joint

The next incarnation of the joint design included two gusset plates, as shown in Figure 14 overleaf. The geometry of the plates was such to promote obvious assembly, and the size and hole spacing of the plates were the main variables to be optimised - the plates ideally would be identical and as light as possible.

Full size models of the joint and tent were built from cardboard to see in 3D how the new design was to fit together. The Eurocode was used to find the minimum centre-to-centre and edge spacing of the holes, and using this and physical layout the positions of the bolt holes were marked on the cardboard model.

2.2.2.1 Plastic Design

A portal frame analysis (from Module 3D3) [3] was done and the Lower Bound Theorem used to make the preliminary selection of angle size and plate thickness, which came out to be 60x60x6 and 6mm respectively. These values were larger than expected, but the design loads included the extra components of a light corrugated iron roof and a considerable lateral load of snow piled up against the sides.

CAD models were created of the joint section; one in ProEngineer and one in RHINO (see Figures 13 & 14 overleaf). The ProEngineer model was made to confirm that the bolt placement would work, and with a view to automating manufacture if the project need many prototypes. The RHINO model was done to showcase the development on the joint at the ShelterMeeting, as these images were used in the ShelterCentre presentation.

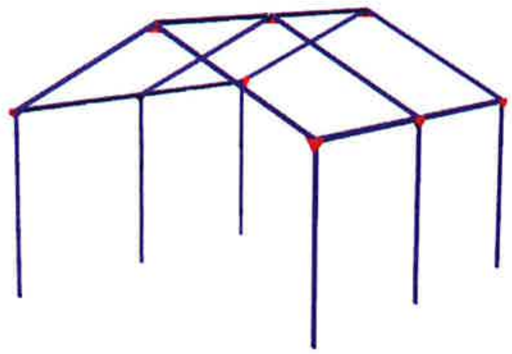


Figure 13: Isometric view of tent frame

Figure 14: Two Plate Joint Close-Up

With the modelling done a full scale physical prototype was made of the joint, with aluminium angles and 10mm caphead steel screws used. The findings of the project to date were brought to the ShelterMeeting [1] conference in Geneva. It was pointed out that the frame would be strengthened by the inhabitants (e.g. by adding tie bars) if they were to add, say, an iron roof, hence there was little need for an overly conservative design. It was suggested to use an engineering plastic in order to meet the 50kg weight limit.

On return to the UK, further calculations were done; the extra load components were removed, resulting in a reduced cross-section and hence a lighter total tent weight. Another model was built from aluminium to this smaller specification (40x40x3 angles & 3mm plate – see Figure 25 in Experiment section for photo) and this time using M6 bolts, as opposed to the M10s chosen originally This reduced size meant the bolt hole placement on this improved such that the plates were identical. A consequence of having smaller bolt holes was that there was less rotation of the angles, as the spacing between the first and last bolt increased. Wingnuts were used in this model, so that the connections could be hand-tightened.

2.2.2.2 Elastic Design

The plastic analysis had yielded a design which had sufficient moment capacity to sustain the loads, one of the ULS criteria (the other being buckling which was dealt with in the final stages of design). An elastic analysis was required to check the SLS criterion of deflection.

The structure of the tent was too difficult to analyse elastically via hand calculations so a finite element computer package was required. Two options were available in the department - Oasys GSA and Ansys. GSA was selected as it was easier to set up, make changes to and experience had been gained with it in Part IIA.

Initially five different sizes of plate (from value h = 0.1m to h = 0.3m - see Figure 15) were input to the programme and the resulting displacements noted for each. For each case the deflections were found to be far too large to be acceptable: of the order of 1m. The programme, however, was not specialised in dealing with aluminium angles, being a fairly standard finite element package, so checks were needed before its results could be confidently given as reasons for a design change.

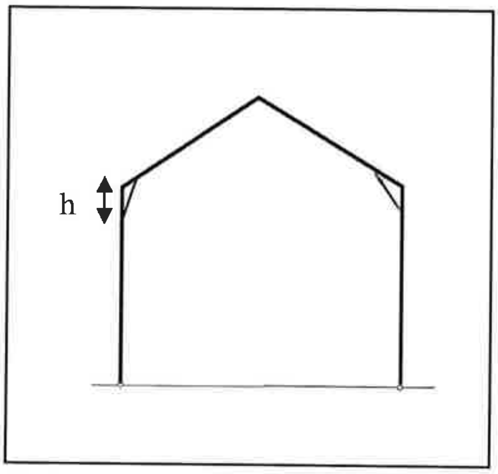


Figure 15: h distance

2.2.2.3 Design Checks

In order to have confidence in the programme's results some hand checks needed to be done. This was done using a 'Ladder' approach in which an understanding of the deflections was built up from simple cases to more complicated ones and on to the full design. Initially very simple cases were considered and the results found by hand and computer and any discrepancies investigated and explained. The next stage was to have more complex 2D models and use a combination of truss analysis and virtual work to investigate them. As the cases became more complex the hand analysis was used to put bounds on the computer results i.e. the hand analysed scenario included simplifications that meant its results were known to be an upper/lower bound on the actual result, so the validity of the computer's results could be gauged. Table 1 below outlines the main stages and results.

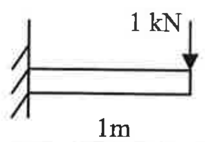
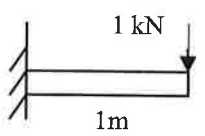
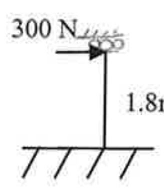
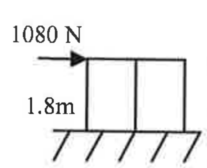
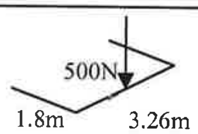
Type	Diagram	Hand Deflection (mm)	GSA Deflection (mm)	Reason for Discrepancy
Cantilever 1 (Loaded at Shear Centre)		230	229	Negligible
Cantilever 2 (Loaded at centroid)		240	238.9	Negligible – this is different to above as values are absolute: include lateral as well as vertical
Column		237	233	Slightly different I value in GSA
2D Frame		569.6	776.9	Hand Result had extra stiffness in joint – a lower bound
3D Frame		1.38	1.399	Negligible

Table 1: Unbraced 'Check Ladder' Progression

The angle sections presented difficulties in calculation due to their asymmetry. Sections like this deflect out-of-plane when loaded. If they are loaded away from their shear centre there are torsional effects in addition to bending [4]. In this case the angles were assumed to be loaded along their centroidal axes, which were not coincident with their shear centres, hence there were twisting effects to be considered as well as the deflections about the two principal axes. As these out-of-plane and twisting effects were non-negligible, it was important to ensure the computer analysis was taking them into account.

Hand calculations became unfeasibly time-consuming in all but the most basic 3D models, so the computer results had to be trusted from here. However this could be done with confidence as the checks helped gain an understanding of how the forces were being carried and also rooted out a few problems in the computer analysis - namely that the pin joints were not being correctly modelled and the torsional twisting inherent in angle deflection was being omitted.

Even with the corrections the computer analysis gave deflections no less than 600mm, which was unacceptable. To reduce the deflections to an acceptable level (generously set at 300mm) would have required large amounts of metal weighing and costing excessive amounts. A design with bracing, outlined in the next section, gave deflections far less than this, so a convincing case was made to ShelterCentre to permit a change in direction to a braced solution, which they accepted.

2.3 Braced Frame

The braced frame concept was mooted at the early stages of the project as an efficient way to carry the loads to ground and to limit deflections. However it was not favoured by ShelterCentre as the cables presented complications for the sheeting and in erection. Furthermore it was feared that as bracing is not an intuitive structural system that inhabitants might remove/alter it.

Only when the unbraced solution was analysed elastically and showed massive deflections was the braced concept revisited. Also bracing would transform the tent from a portal frame action to a truss action – meaning less moments and shear forces. As the tent was to have only one section type and length, rigid bracing sections could not be used. Instead cables were proposed as these were light, easy-to-pack and could be replaced on site by ropes if needs be. A simple bracing system was devised that suited cable capabilities.

2.3.1 Longitudinal Bracing

The longitudinal bracing was the first to be tackled, and a traditional design tried out (see Figure 16) with diagonal cables placed in the planes of the walls and roof. This was analysed in GSA and checked via the 'Ladder' approach outlined above, with the results in Table 2 overleaf. It was found that the bracing reduced the deflections by an order of magnitude when compared with the unbraced model. As expected the moments and shear forces were everywhere reduced so that a smaller 30x30x3 angle could be used, and that the joints could now be simple bolted arrangements with no gusset plates as no moment resistance was needed.

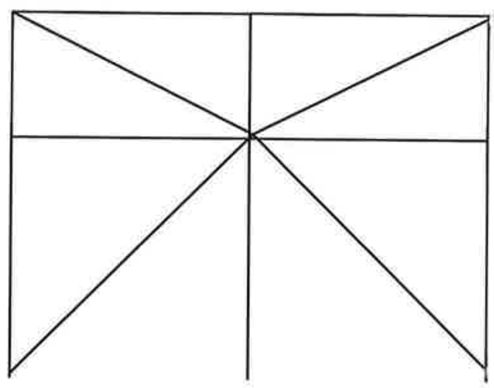


Figure 16: Side View of Longitudinal Bracing

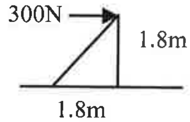
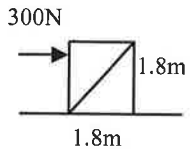
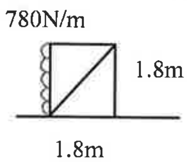
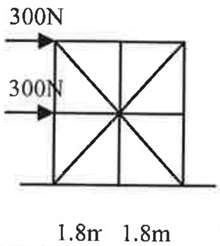
TYPE	DIAGRAM	HAND DEFLECTION (MM)	GSA DEFLECTION (MM)	REASON FOR DISCREPANCY
Triangle		0.12	0.128	Negligible
Single Bay		1.1	1.114	Negligible
Single Bay Distributed Load		50	50.8	Negligible
Two Bays & Roof		1.62	1.702	GSA gives higher value therefore conservative - OK

Table 2: Braced 'Check Ladder' Progression

In addition to the analysis, the final report from a similar project a few years ago was read. This project used the same dimensions and loading but its members were square hollow sections. The report concluded that bracing should be investigated as its final design was unbraced and too flexible [5].

Once the benefits were quantified and presented, the change to the braced design was given the go ahead.

2.3.2 Lateral Bracing

ShelterCentre were reluctant to allow bracing in the end bays to achieve lateral bracing as these bays were the entrances and needed to be kept clear. Analysis suggested that without lateral bracing very substantial haunches would be needed in these bays, again pushing up tent weight and cost, so an acceptable bracing scheme had to be devised.

After some consideration concepts were generated, two of these (see Figure 17) were deemed possible and were analysed using GSA. These were proposed in a report sent to ShelterCentre. To prevent the doorway becoming blocked, pegging two cables to ground using long pin-like steel pegs were suggested as the best solution (see Table 3 overleaf). Unfortunately the solution was unacceptable as there were numerous difficulties with pegs: soil conditions often do not allow pegs; pegs tend to trip children and cut their feet; embedding pegs properly is arduous and often not done; even if they are properly anchored they come loose with time and get lost. The other solution (BF1) was invalid as it deflected too much.

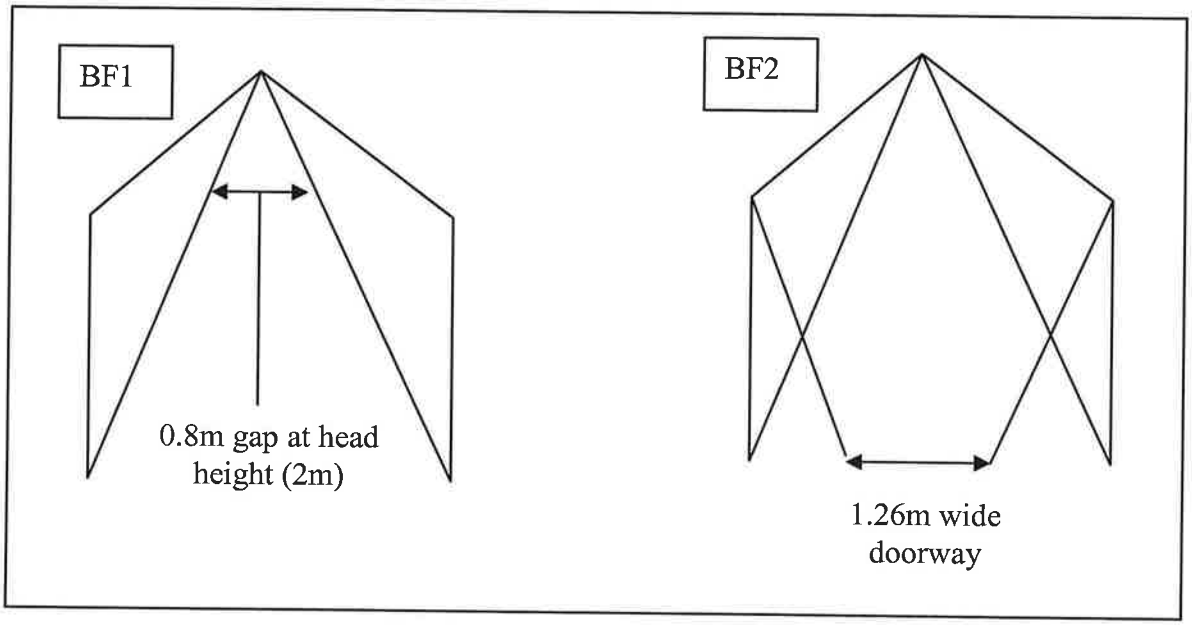


Figure 17: Initial Endbracing Concepts

TENT NAME		LATERAL DEFLECTION (M)	LATERAL MOMENT (NM)
Unbraced Frame *		0.87	872
BF1		0.4	766
BF2		0.005	135
* included for comparative purposes			

Table 3: Initial Endbracing Calculations

To resolve this issue, four further designs were devised with ShelterCentre that were suitable and didn't require pegs (see Figure 18 overleaf). Of these two (BF8 & BF9) relied heavily upon cable mechanisms and could not be satisfactorily analysed by GSA, rather a dynamic relaxation programme would have been required. This could not be done as this analysis would have been too lengthy, and also as the theory behind dynamic relaxation is complex so gaining sufficient understanding to have confidence in the results would have taken further time. Finally the tent ideally should not rely on cable interactions for its integrity – cables are often tripped over and used to hang washing etc.

The other two designs were very similar; the only difference being BF7 used cable interaction whilst BF5 did not. Surprisingly the analysis showed only a very slight advantage in allowing the cables to interact (only a 0.2mm reduction in deflection). This small gain was not worth the added complications in analysis and construction so BF5 was chosen as the lateral bracing design and was incorporated into the final design, which now met the SLS deflection limits imposed in every case.

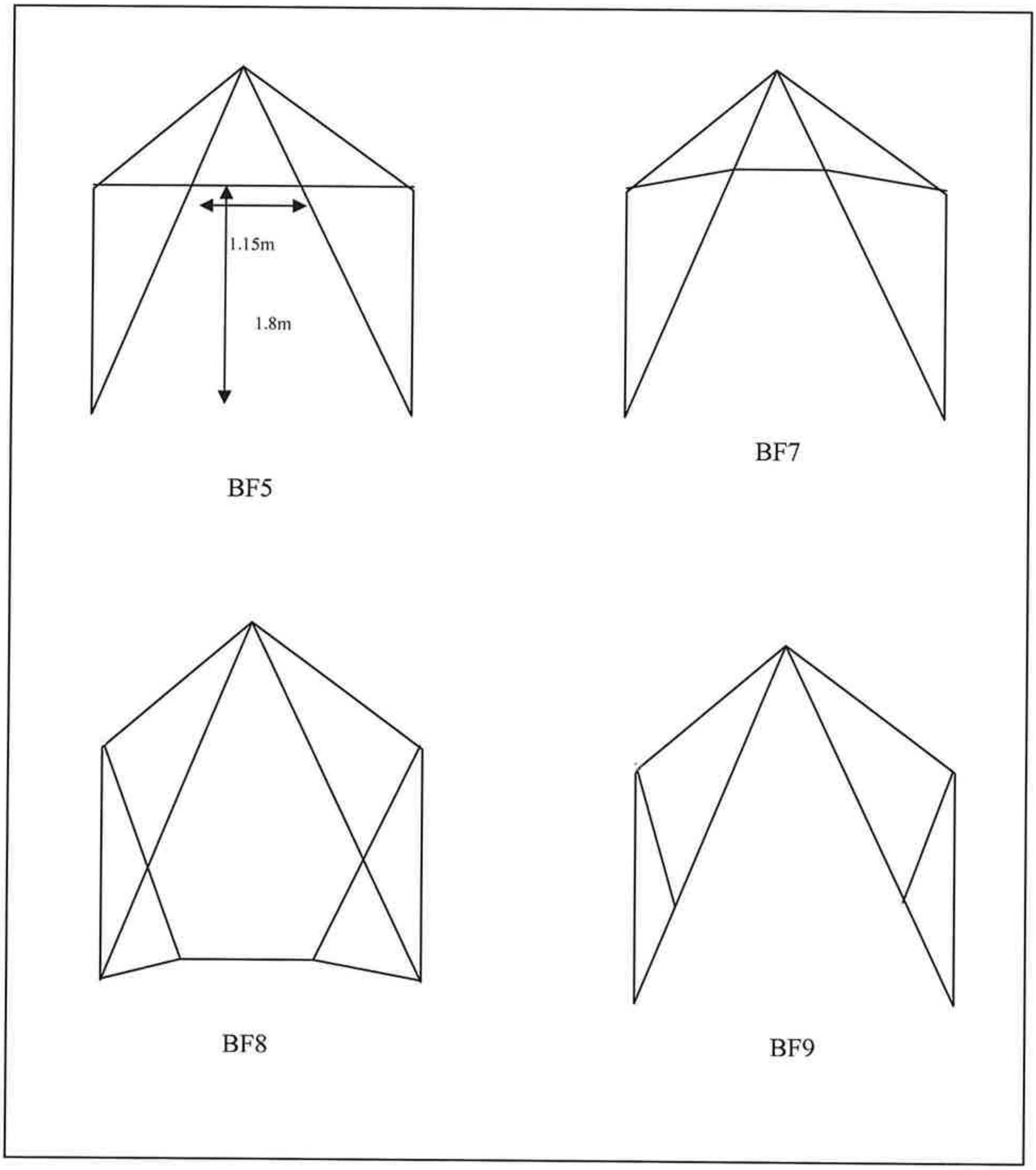


Figure 18: Acceptable Endbracing Designs

2.3.3 ULS Checks

Once the design of the tent had been finalised and SLS limits met, the next stage was to check the ULS performance of the frame. GSA was used to find the stress distribution within the frame for both ULS scenarios (wind blowing laterally and longitudinally) and the components checked against the failure criteria.

First the axial capacities were checked; from Axial Force = Stress x Cross-Sectional Area, it was investigated if each component had sufficient cross section to sustain the axial force. The members were found to be satisfactory but the cable diameter had to be increased from 3mm to 4mm.

The moment capacity of the angles was then examined. To begin with the ultimate plastic moment of the section was found and compared with the moments generated in loading. The latter were not large as all the joints are pinned. Then it was realised that as moments were present in two directions, there would be interaction effects. An interaction diagram was derived (see Figure 19 below) and from this the moments were not found to cause failure.

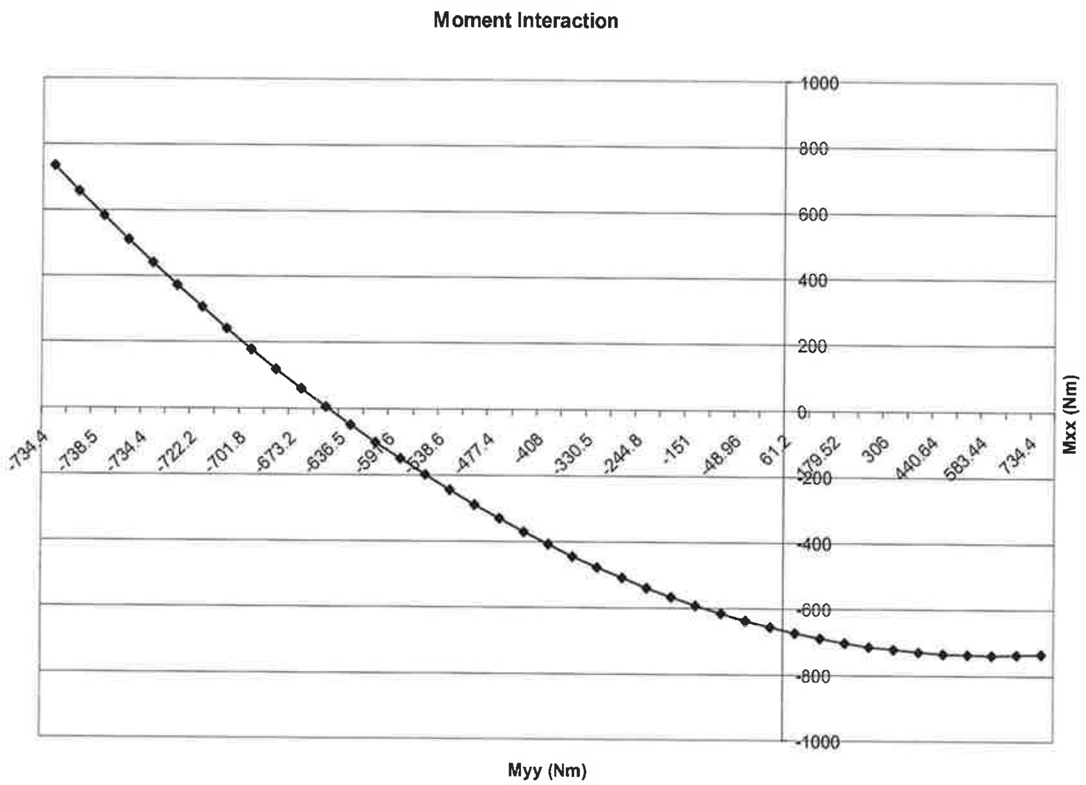


Figure 19: Moment Interaction Diagram for 40x40x4 Aluminium Angle

Buckling was the final ULS check. Angle sections have a very weak axis v-v, highlighted in Figure 20 below, about which buckling would occur as this axis was not restrained. To make matters worse aluminium is a relatively flexible material which is susceptible to buckling. This problem was encountered previously in the Part IA Structural Design Project [7], and was dealt with via Buckling Design Curves. An Euler Buckling calculation showed that the angle members were extremely slender and would buckle. These results agreed with the IA Design Curves.

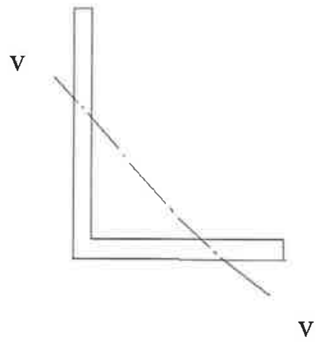


Figure 20: Weak v-v Axis of Angle Section

It was found that the effective length of the members needed to be 1m or a 40x40x4 section was required to prevent buckling. Adding further bracing was another option to prevent buckling. This was undesirable as it further cluttered the design and left more room for error in construction. Also the increased member section boosted strength and redundancy, but with the drawback of a 50% increase in weight. The Euler buckling curve for the 40x40x4 aluminium angle section is shown in Figure 21 overleaf.

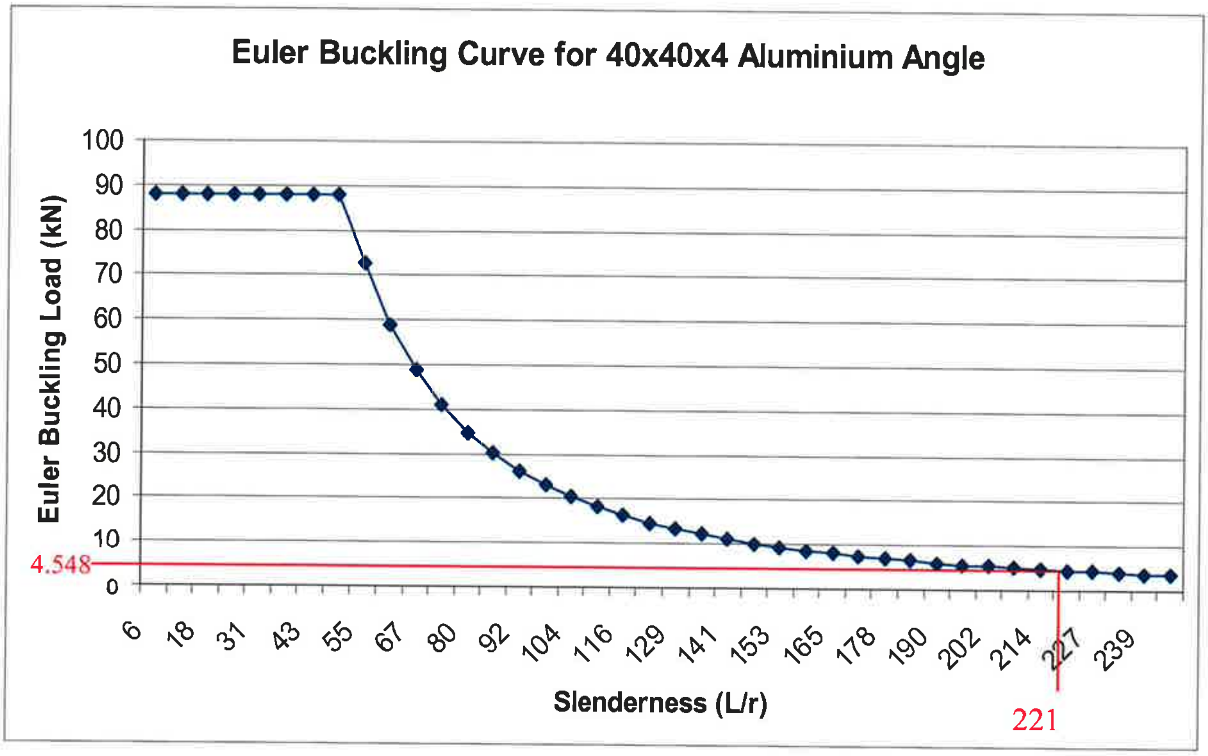


Figure 21: Euler Buckling Curve with Chosen Slenderness Marked

2.3.4 Scale Model Analysis

Once the final design had been completed, it was decided to construct a quarter-scale model so that the real-world performance could be compared with the GSA predictions. The model was input into the GSA programme and analysed under the same loads that the physical model was. The results for this are included in the experimental results section for ease of comparison.

2.4 Bolts & Joint Detailing

The bolts were first checked whilst making the first (unbraced) joint prototype. Checks were made against failure in shear and bearing, and it was found that 3mm diameter bolts would more than meet the requirements. Bolts of this size would be too small to be practical – they would be difficult to tighten and would be easily lost. Instead 10mm bolts were arbitrarily chosen initially. After consultation with ShelterCentre and seeing the bolts available in the Pakistani marketplaces, 6mm bolts were decided upon.

The joint detailing for the braced frame was more difficult as there were no plates hence less space available to place bolts. From Structural Steelwork lecture notes [7], a bolt-centre-to-edge spacing of 2.5φ (where φ is the bolt diameter) was taken. An aluminium design guide [6] allowed a spacing of 1.5φ, so this was used wherever 2.5φ could not be. Comprehensive full sized drawings were made of each joint so that the location of each bolt was known. It was found for the 30x30x3 EA there was insufficient space, so a gusset plate was needed (the bolts could not meet both the capacity and space requirements). Fortunately when the cross-section was increased to 40x40x4, the extra space just allowed a satisfactory bolt arrangement, which is shown in Figure 22 below and Figure 23 overleaf.

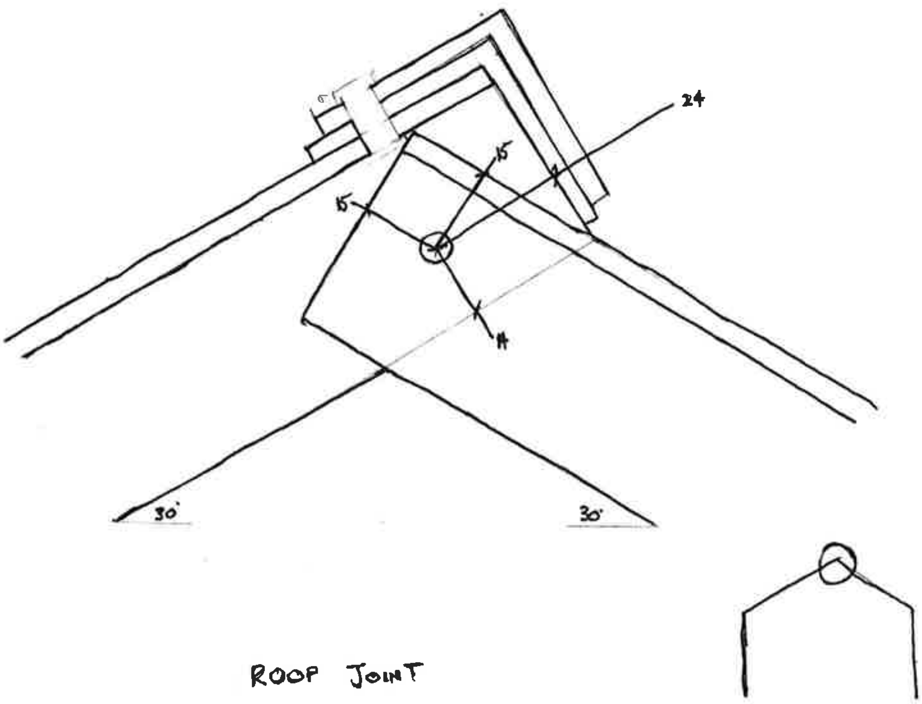


Figure 22: Drawing Detail of Roof Joint

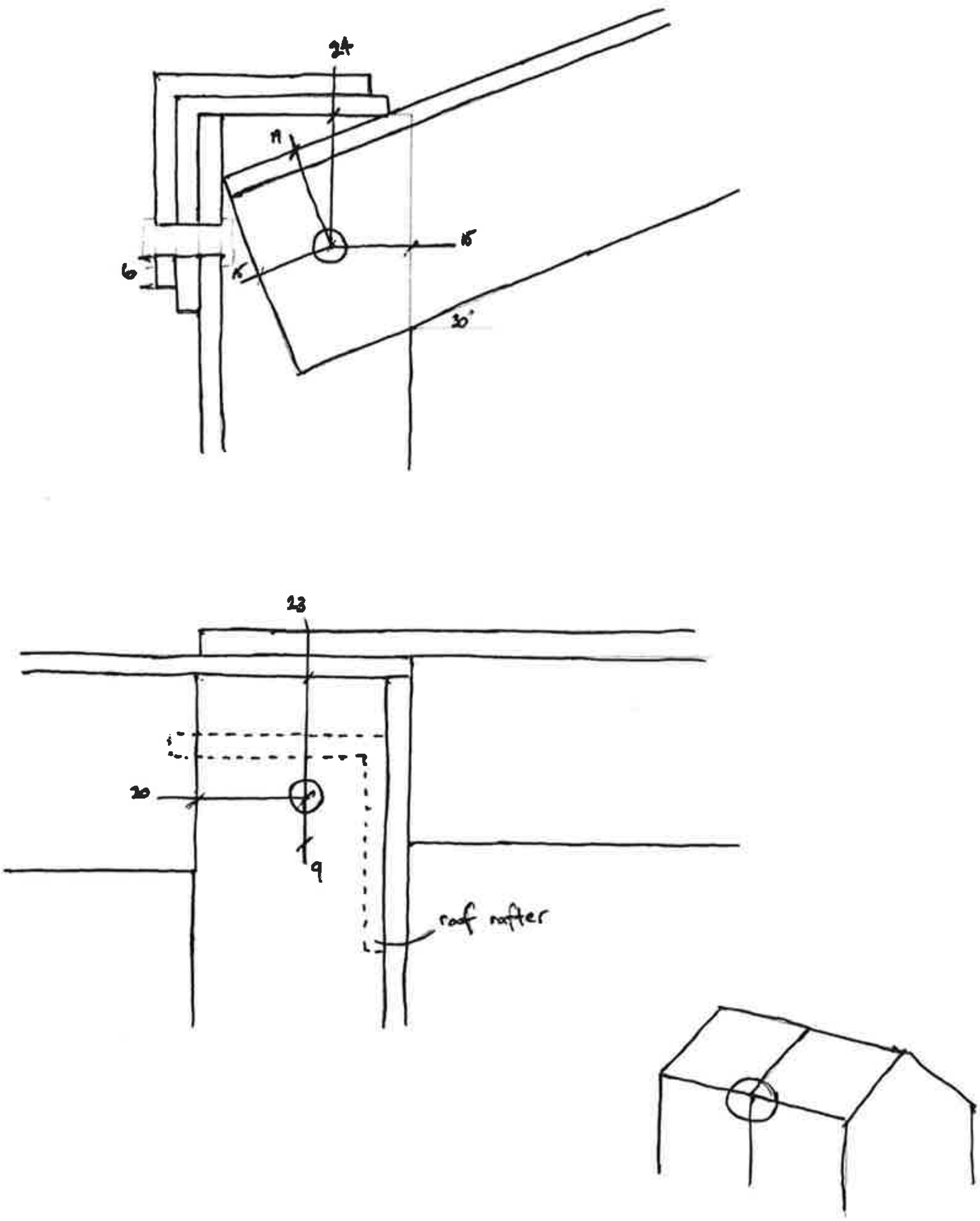


Figure 23: Side & Front Elevation Joint Layout Drawings for Central Joint

In both above figures, all dimensions are in millimetres, the angle sections are 40x40x4mm and the bolt holes are 6mm.

2.5 Material

Part of the brief from ShelterCentre was to find the optimum material for the members. This needed to be finalised in early Lent so that the scope of the project became narrow enough to be completed before the deadline. The main considerations were strength, stiffness, cost and weight, with volume and corrosion resistance being secondary factors. The steel, aluminium and engineering plastics were identified as the three main alternatives and were tested against the criteria.

Steel was found to be too heavy despite its strength and cost, and rusting was also a disqualifying concern. Engineering plastics (such as CFRP, GFRP, polycarbonate) were examined and compared favourably on many fronts; being light, strong, corrosion resistant and reasonably stiff. However holes would have to be drilled in them, breaking the fibres which are their source of strength, and they are also not as well understood as more conventional materials, though research is being done. These concerns were surmountable however, but it was the high cost of such plastics which removed them from consideration. Building a tent from them would easily break the $400 budget set out, but also storing any number of these tents would provide a target for thieves and it has been known for entrepreneurial refugees to sell their tents if the materials are worth a considerable sum, which is undesirable. The third option examined, aluminium, was found to a good middle ground – quite light, reasonable strong and not too expensive, as well as resistant to corrosion. Concerns were raised about its stiffness, especially when in angle form which is a complex phenomenon, but these could be dealt with via good design, and so aluminium was the selected material.

2.6 Analysis of Pakistan Data

Immediately at the start of Lent term the data gathered in Pakistan was analysed. This involved identifying broad categories of tent, working out some of the structural values (second moment of area and plastic modulus – see Table 4 overleaf) for each tent and comparing these to the user-evaluations. Unsurprisingly the tents with a sturdy frame and therefore less leakage and deflection were the most favoured, being highly sought after in each camp. This correlation was reinforced with the opinions of the canvas tensioned tents – those which relied heavily upon canvas tension and had few members were more difficult to live in that those which had more members and less prestress. Interestingly a range of second moments of area were recorded, and there was little correlation between these and the performance of the tents. This was confirmed by interviews with NGO officials who said that bar sizes were chosen based on convenience – what was cheapest and easiest for the manufacturer – as opposed to any structural concerns. The result was bar diameters inappropriate to the design and task. Worryingly when tents did fall over, the inhabitants blamed the bars and demanded new ones, even though the actual cause was poor tent design which left stocky sections unsupported. This can be contrasted to the handful of well thought-out tents, one of which used extremely slender Rectangular Hollow Sections but was one of the most robust tents on the site.

Analysis of Table 4 revealed that the average second moment of area in a tent deemed 'good' was 47853 mm^4, and corresponding average plastic modulus was 4425 mm^3. It is encouraging that the final values arrived at by this project are 45300 mm^4 and 1510 mm^3. The former of which is reasonably close, implying there is sufficient stiffness; and the latter is smaller, implying efficiency as there is less material but the structure is known to be safe up until the design loads. These are not large values, and many tents that were described as miserable had sections greater than these, showing that poor tent design is a root problem.

The other conclusions drawn were: the practical importance of water proofing, best done by providing a robust tent frame; the paucity of workshop facilities and market selection in the remote areas where disasters tend to have worst effect; the long timescales involved in rehousing refugees, and the requirement to have a tent that can both endure and be readily repaired and upgraded.

Name	Type/Category	Width (m)	Length (m)	Number of Poles	Height (m)	Pole Diameter (mm)	Pole I (mm^4)	Pole Z (mm^3)	User Verdict
Turkish Lighthouse	Dome	3	4.5	10	2	20	9425	942.48	Very Good
ILAP	V	3	4	3	2	25	18408	1472.62	Miserable
Army Childcare	House	5	8	20	3				Good
UNFPA	House	4	4	9	3	15	3976	530.14	OK
Italian Civil Defence	House	3	4	10	2.2	15	3976	530.14	V good, aluminium CHS
IFRC	V	3	6	13	2	20	9425	942.48	V Poor
Caritas	Dome	5	8	15	3	10	1178	235.62	good
Unicef Office	House	5	8	17	3	25	18408	1472.62	OK
UNHCR	V	3	4	3	2	25	18408	1472.62	poor
Tamimi	House	3	3	13	3	40	75398	3769.91	poor
Unicef Office	V	3	10	16	2.2	25	18408	1472.62	poor
CB&I	Dome	5	4	23	3	30	31809	2120.58	V good
KLH	House	5	10	13	`3	25	18408	1472.62	poor
Mosque	V	10	30	45	4	40	75398	3769.91	Solid but leaked
Oxfam	Dome	6	6	11	3	50	147262	5890.49	Excellent
Nikki	V	4	4	3	2	50	147262	5890.49	Poor
TDH	Circular	12.2	3	9	2.5	35	50511	2886.34	Poor
Turk Kizila	House	4	3.4	9	3.26	50	147262	5890.49	OK
Blue	Dome	3	6	7	2	30	31809	2120.58	
Hire.com.pk	House	3.2	3.2	9	2.5	20	9425	942.48	Good
Army Family	V	2.8	3	3	2	40	75398	3769.91	Poor
Japanese NGO	V	3	4	3	2	50	147262	5890.49	Very Poor
Army	V	4	4	3	2.5	30	31809	2120.58	Poor
US Army	House	6	6	9	4	90	858833	19085.18	Excellent

Table 4: Pakistan Data & Analysis

2.7 Other Considerations

There are many issues which have not been discussed that impinge on the assumptions above and the frame performance. These have been analysed briefly to check that there is no major fault that will stop the project, but in future there might be cause to investigate these matters further.

2.7.1 Support Conditions

The project assumed pin jointed supports at the ground/ leg interface. This is an improvement on previous projects that assumed fixed joints and lead to a more robust design. The proposed anchoring system is that the sides of the canvas will have pockets in them, into which stones can be placed to anchor the tent. Furthermore the legs will be dug slightly into the top soil.

Using some simple analysis [8] it was calculated that a loose sandy soil could provide the maximum required vertical reaction (approx. 2 kN) without any embedment. As this is one of the weakest soil types and any embedment would increase the capacity, it can be assumed that the vertical support is satisfactory. For horizontal support the tent is heavily reliant on the stone pockets, as it would take embedment of 800mm in the same loose sand to generate the required reaction.

If the stone pockets alone take all the lateral loading at the base then the force in the sheeting is estimated at 398 N, which is deemed just about acceptable for the thin plastic used. Any higher stress and the sheeting would tear. It is thought that if properly constructed this scenario will not occur as the frame should take the force before the sheeting does.

2.7.2 Dynamic Effects

The buffeting of the wind load was not quantitatively considered. Cyclic motion will at least cause the bolts to loosen (this is why wignuts were used – they can be easily hand tightened) or at worst cause fatigue failure in the angles at the joints. The effect on the canvas will also be considerable – sustained rubbing against any metal edge will wear away the fabric and let water in. It is proposed a rubber barrier be put on the joints to prevent this occurring, and that the sharp edges of the angles be ground off.

3. THEORETICAL RESULTS & DISCUSSION

Table 5 below shows the progression of the design, and gives the main reason for change at each main stage.

STAGE	ANGLE SIZE	MAIN PROBLEM
Single Plate Joint	60x60x6	Plate too weak in bending
Two Plate Joint	60x60x6	Too heavy
Refined Two-Plate Joint	40x40x3	Deflected too much
Initial Braced Design	30x30x3	Deflected too much laterally
Second Braced Design	30x30x3	Buckled under load
Final Design	40x40x4	

Table 5: Design Progression

3.1 Results

Table 6 below gives the maximum values for the final design.

Parameter	Value under Lateral Loading	Value under Longitudinal Loading	
SLS			Max allowable:
Deflection	23.5mm	5mm	300mm
ULS			Capacity:
Cable Axial Force	3227 N	1266 N	4460 N
Angle Tensile Force	22.4N	-	88000 N
Angle Compressive Force	4312 N	1697 N	4548 N
Moment xx	209 Nm	163 Nm	734 Nm
Moment yy	94 Nm	252 Nm	734 Nm
- Moment Interaction also checked and was found to be OK			
Shear Force	466.2 N	560.7 N	47111 N

Table 6: Final Design Values

3.2 Discussion

The design was the main bulk of the project. As the findings of the project may be implemented in the real world, it was vital there were thorough checks at every stage so that there was confidence in the final product. The main challenge was in overcoming the constraints in design; the more obvious and basic ways of optimising the design from an engineering point of view were often incompatible with various factors (social, ergonomic, construction, etc.) so other solutions had to be found. The final design represents a good compromise between good engineering and these other issues.

The design is entirely comprised of angles, cables, nuts and bolts. These are inexpensive building materials and that are also easy to pack to minimise volume. Additionally these components are readily available in most, if not all, corners of the globe in markets and workshops, and this ease of access to spare parts means broken parts can be sourced and replaced easily. Furthermore if a part only minorly damaged, or arrives with a flaw (e.g. missing a bolt hole) then workshop facilities in most countries are sufficient to be able to repair this. In addition these facilities can be used to upgrade the frame – e.g. cut extra members or drill bolt holes – so that the tent's life can be prolonged. A final benefit of the component choice is that if there is not an adequate number of official tents then copies can be built if the parts are available.

The design is extremely simple, the holes are drilled such that once a person knows what the final shape should be; it is merely a matter of finding the pieces that fit together and sliding through the bolts. No tools are required to put it up and with each member weighing just over 1.5kg no heavy lifting is necessary.

The design is heavily reliant on GSA analysis and theoretical checks to back this up. Effects outside the idealisations of these approaches have not been well investigated; namely the possibility of failure due to buffeting, sliding or overturning failure in the supports, or failure due to imperfect construction. The first two scenarios require some specialist analysis, as both mechanisms are not fully understood. Incorrect construction has been somewhat dealt with in the buckling calculation – the curves allow for some imperfections – and also in the slight conservative nature of the design overall, which covers all the effects to an extent. Nevertheless it is recommended that these be further looked into before a rounded explanation of tent failure can be claimed.

The major bane to refugees' lives witnessed in Pakistan was that of water leaking into the tent. This was not directly addressed in the project, as it is thought that leakage is symptomatic of other more fundamental problems and by tackling these in an improved frame design, this fault will be stopped.

The main problem with the final design is that it is dependant on the cable bracing system for much of its stiffness. If this is not correctly installed and maintained then the tent risks becoming a mechanism. As highlighted during design, bracing is not a structural system that is immediately intuitive to a lay person, indeed the lateral bracing action used in the tent was not obvious to an undergraduate engineer. Bracing is a construction form seldom seen in the developing world and there is a considerable risk the constructors of the tent may deem it surplus or just not understand it enough to install it. Even if set up correctly, the cables will need to be kept taut to work, otherwise the tent will deflect unimpeded until the cables are taut, hence the inhabitants will need to periodically re-tension them as cyclic loading will cause the cables to become loose. These issues can be overcome by some training running in parallel with the tent distribution. This already goes on so would not be a main change, and there are usually some engineers or people with a technical background on site from time to time who will hopefully correct any problems that arise. Also useful might be a diagram of the finished tent with specific instructions on tensioning the bracing to emphasise the point.

As mentioned in Section 2.7.2 the effects of cyclic loading have not been considered by this project. The gusting nature of the wind makes this loading scenario a certainty and it can cause loosening of cables and bolts, fatigue at stress concentration points and failure in the covering. It is not know the extent of these effects, though in the field the latter is extremely visible, and more tests should be carried out to see if a different connection or tensioning system is needed, or the extent sharp edges need to be removed.

4. APPARATUS AND EXPERIMENTAL TECHNIQUES

The project was more concerned with thorough design than experimental methods, however there were prototypes made to ensure the designs were realistic and buildable, and to detect any unthought of effects or considerations. To this end the experimental end of the project was successful.

4.1 Cardboard Models

As mentioned in Section 2, two cardboard models were made in the initial design stages to help with problem visualisation and detailing. Both were successful in bringing the drawings and calculations into the real world.

The first one was a cardboard model of the two-plate joint. Its purpose was to show the layout and how the four angles, two plates and eight bolts would fit together and ensure the bolts did not interfere with eachother.

The second cardboard model was a 1:10 scale model of the full tent (shown in Figure 24 below). It was made from thin cardboard stapled together and the main purpose was to show the overall configuration – how the angles needed to be oriented to best fit together. Furthermore it gave an idea of the relative dimensions, and together with the first model, it was fundamental in figuring out the roof apex joint, which did not carry much moment but was awkward and unobvious due to the geometry.

Figure 24: 1:10 Cardboard Model

4.2 Two-Plate Joint Prototypes

As stated previously, two full-scale model joints were made using aluminium plate and angles with steel bolts. The first (60x60x6 EA with 6mm plate) was made to demonstrate the concept at the ShelterMeeting, as well as to check geometries and manufacturing ease. The second (40x40x3 with 3mm plate), shown in Figure 25 below, was a refinement on the first, attempting to overcome some of its errors.

It was extremely useful in highlighting problems not considered/present in theory - small tolerances in the bolt holes allowed substantial rotation of the angles even when bolted in. In reality this could cause the tent to shake the bolts loose and fall to pieces in windy conditions and to prevent this more bolts spaced further apart were needed.

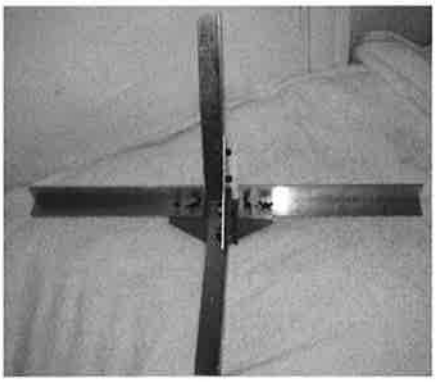


Figure 25: Second Aluminium Prototype

4.3 Quarter Scale Model

Once the design was finalised it was decided to build a quarter scale prototype and test it briefly to see how the real deflections compared with the computer predictions.

Once space was available in the workshop the work commenced. Fortunately the Part IA Structural Design Project had taught most of the relevant techniques – the 9.5x9.5x0.8 mm aluminium angles were quickly cut and riveted together using 1.5mm pop rivets. 1mm diameter Metal Inert Gas Welding wire (mainly mild steel in composition) was used to model the cable, which was threaded through holes drilled near the joints.

The prototype was tested by placing weights on a tray connected via a pulley to points on the frame, and using a ruler to measure deflection at those points (see Figure 26).

Figure 26: Experimental Set up

The model was loaded in four places – Roof Centre, Roof End, Centre Haunch, End Haunch – as marked in Figure 27 below. When a given point was to be tested, a string was tied to it. The other end of the string was looped over a pullet and loaded by putting weights onto a tray. The displacement of the load point was measured by eye with a ruler held in position. The loads were chosen from trial and error – loads of over 10 N gave large deflections and cause the supports to fail laterally. Loads less than 1 N gave deflections that were smaller than 1mm and therefore difficult to read by eye.

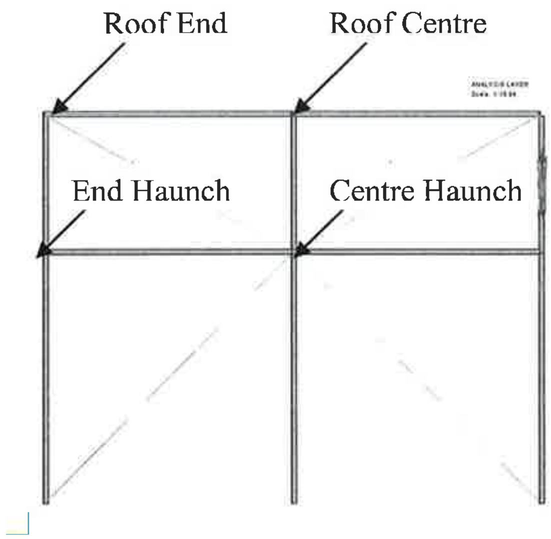
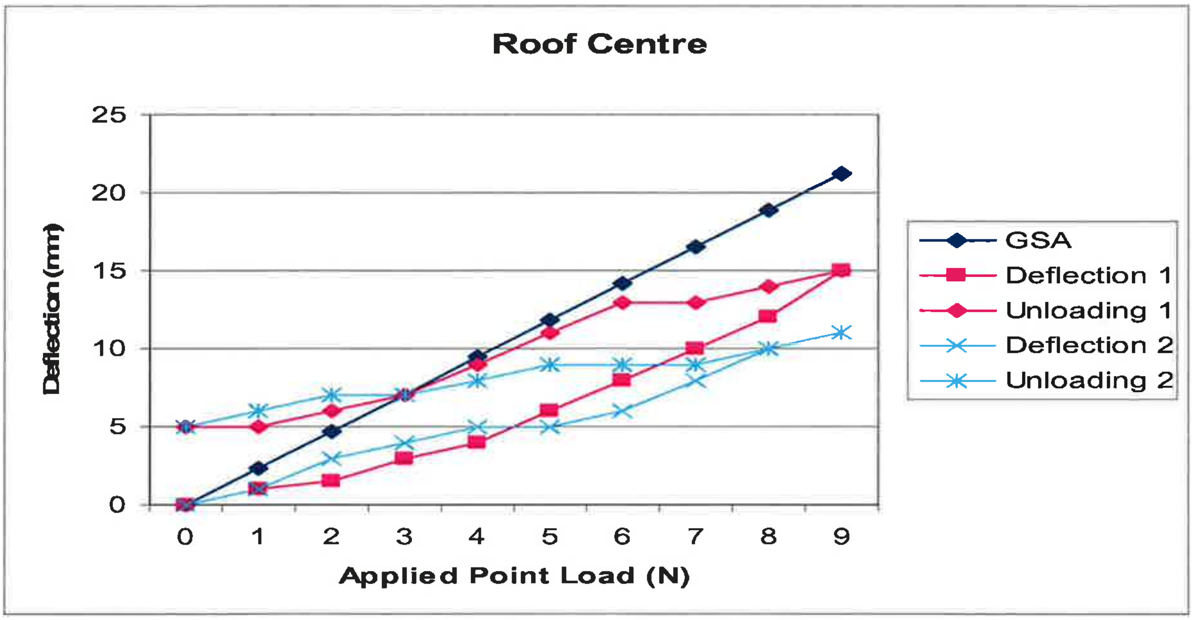


Figure 27: Side Elevation of Model showing Loading Points

5. EXPERIMENTAL RESULTS & DISCUSSION

The graphs of the results from the experiment are given below in Figures 28 & 29. Included in these graphs are the values calculated by GSA for displacement under the same loads.



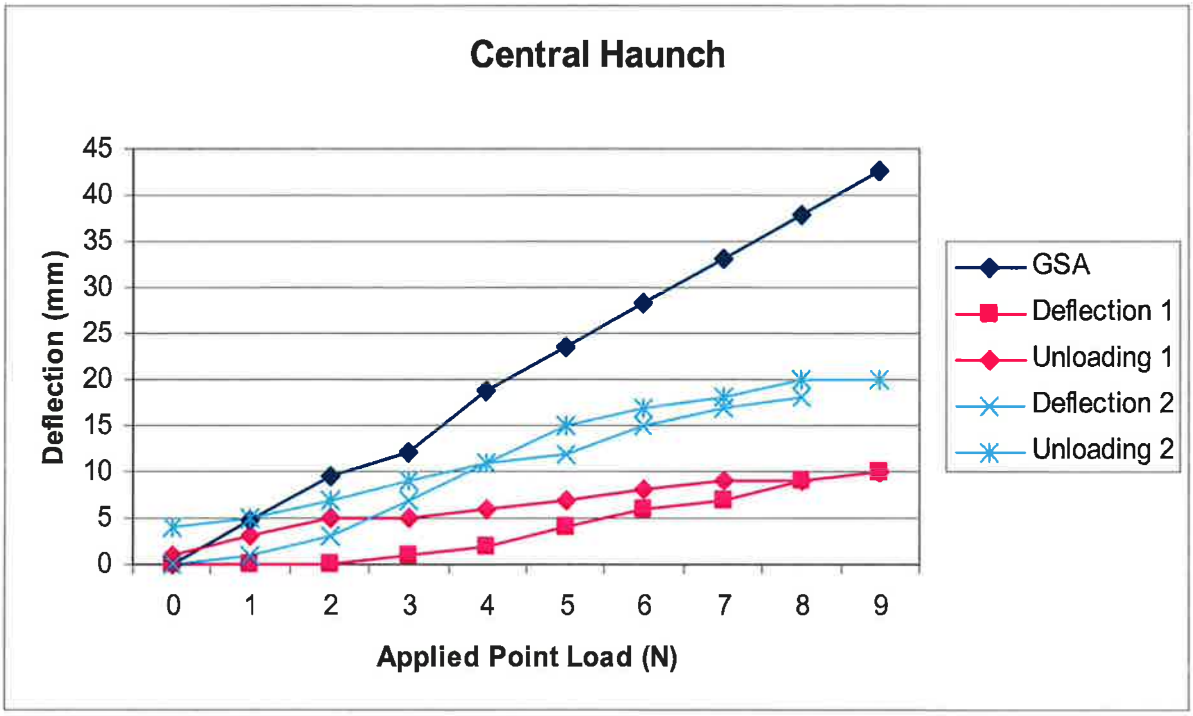


Figure 28: Load vs. Deflection Graphs from Experiment & GSA Analysis for Central Loading Points

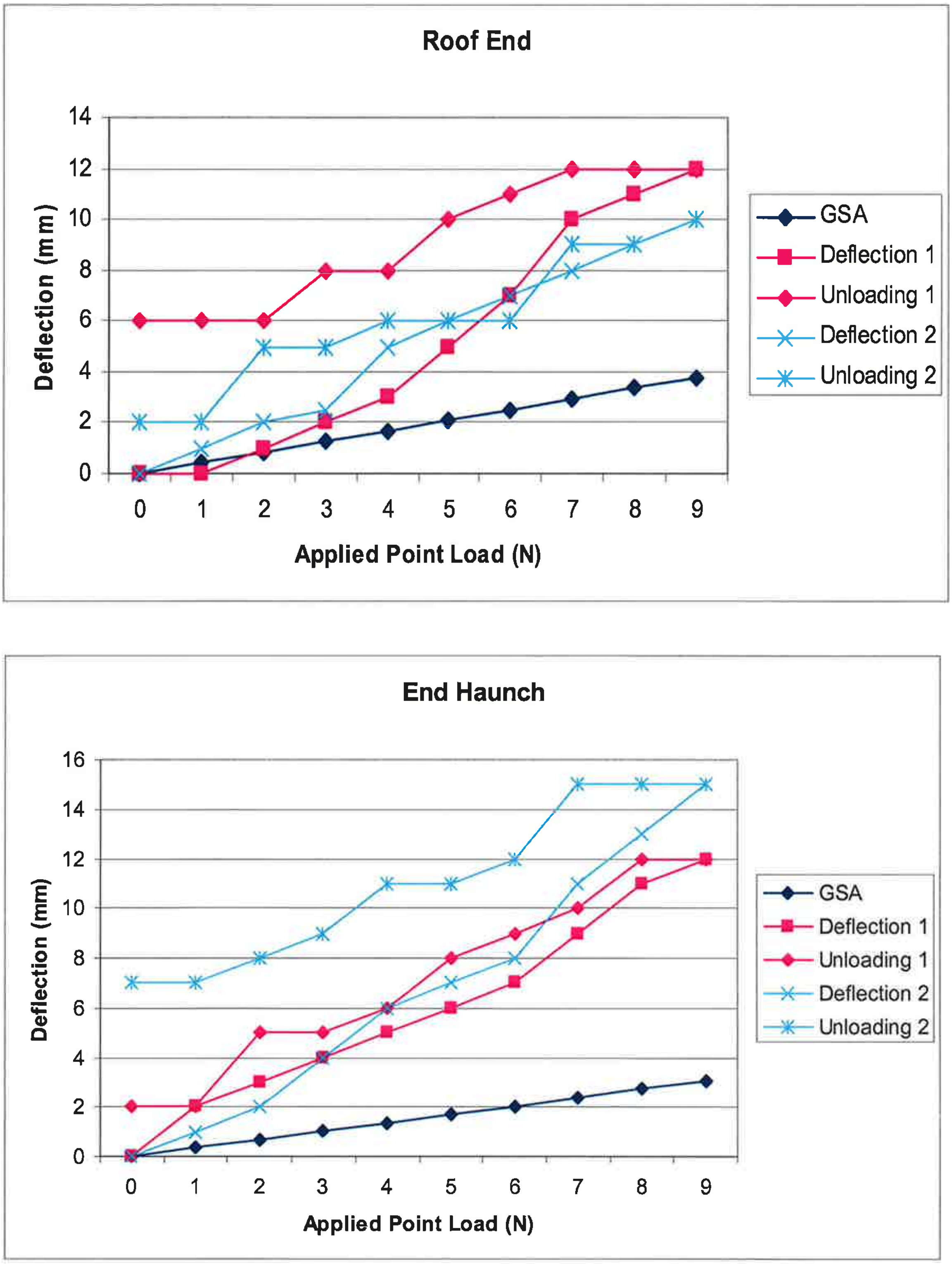


Figure 29: Load vs. Deflection Graphs from Experiment & GSA Analysis for End Loading Points

5.1 Discussion

The experiment was important in tying the theory to reality and in checking how well the computer and physical models related to one another. Unfortunately the results from the experiment were ultimately inconclusive, and ideally a more sophisticated, or indeed full-scale, model would have been built and tested in a more robust manner. Time, however, was not sufficient for this to be done.

The construction of the model tested the joint layout drawings and proved they were valid. The anchoring of the cables had not been so well thought through, which resulted in some minor changes to the design. Visually the finished model emphasised how slender the members were – reassuring as buckling was determined to be the critical failure mode. The structural action was tested by applying loads in various directions and seeing what cables tensioned. In every case the expected action was confirmed, which was important as some of the load paths (especially those involving the lateral end-bracing) were non-obvious and this verification lent weight to the theoretical results.

The riveted joints allowed much rotational freedom but this was limited by the joint geometry, so there was more stiffness than in the analytical model. The addition of the cables to the frame improved the rigidity immensely, stressing their importance. However the MIG wire (used to model the cables) was stiffer than expected and could not be clamped, instead it had to be wound around the angles to tighten it. Another problem with the model was its supports - the legs were merely grounded in lumps of plasticine instead of being properly pinned. Again this was a combination of design oversight initially, combined with a lack of time to properly solve the issue once it was noticed. This arrangement meant the cables could not be properly tensioned as the plasticine would fail if too much lateral force was applied. This created another discrepancy with the computer model. However the reality is more like the plasticine as the supports will not offer infinite lateral and vertical resistance, so this outcome is not entirely adverse.

While testing the model it was noticed that the structure tended to deflect and then 'lock in' to a new position. This is reflected in the unloading curves, where deflections do not return to zero for zero load. This is because the structure has numerous stable configurations and switches between them when moved. This effect was exacerbated by the support arrangement: the plasticine was found too weak to restrain the model laterally on the Structures Lab floor;

hence it was decided to fit the legs inside the holes in said floor as this provided a reasonable pin joint when used with plasticine. The holes were spaced at ~425mm centre-to-centre, whilst the supports should be at 450mm spacing; therefore the model was initially slightly crooked for the tests, which was far from ideal. To try to offset this inaccuracy, the cables were adjusted so that they were still taut. Another possible source of error in testing is the crude method of deflection measurement – this was done by eye and was only accurate to +/- 0.5mm.

There was discrepancy between the GSA-generated deflections and those found in experiment, as seen in Figures 28 & 29 in the previous section. The readings taken for roof centre and centre haunch (Figure 28) were less than GSA predicted which is encouraging as this implies GSA is conservative. However the experimentally found deflections for the roof end and end haunch loading points (Figure 29) were considerably larger than those found by GSA, this implies the opposite – GSA had underestimated and therefore cannot be trusted. The truth is difficult to ascertain as the flaws in the model outlined above are considerable, and also the differences between the real and computer models significantly affect their results. In general the slopes of the lines agree well once the initial lack-of-fit and slackness in the physical model have been overcome. This implies that the structure is behaving more-or-less as expected once the flaws in its construction are overcome, and further suggests that the GSA results are reasonable.

The centre frame was different to the end ones as its feet had no cables attached and the support was observed to be stiffer when removing them, to the extent that they might be considered fixed compared to the other supports. Also the roof cables were more taut than those fastened to the legs as the legs would deflect if too much tension was applied and there was no corresponding problem in the roof. The structural action was such that the centre loads were carried by the entire frame, whereas the end loads were taken by that end bay mainly.

As mentioned, the joints were not truly pinned, but rather could rotate before the angles locked against one another. This effect would add stiffness to the model and reduce deflections. The stress path in the centre loadings was mainly through portal frame action in that bay, with a proportion of the load also being carried to the end bays and brought to ground through the angles there. This path used only the only cables in the roof and angles, and not the other cables which were deemed suspect. Indeed it could be seen visually that the rood cables tensioned more under loading than the end cables did when they were loaded.

Another contributing factor already mentioned is that the centre supports were uncluttered and performed better. All of these effects explain why the centre-loading deflections were less than GSA predicted and why the end bays did not show similar results.

Despite the lack of good correlation, the experiment was useful in confirming the design was realistic and used the load paths predicted. That the results were in the correct 'ball park' was also positive and the problems with the model were not unlike those to be encountered in the field (inexperienced labour, rushed construction, imperfect support conditions) so the adequate test performance added further confidence to the design.

6. FINAL DESIGN

The end product of the project (shown in Figure 30 below) is a straightforward design that utilises a bracing system to efficiently bring the loads to ground. The bracing reduces the required moment capacity of the members, decreasing their minimum cross-section and hence weight, and also allows for simple connections at the joints. This simplicity permits quick construction by inexperienced persons, as well as uncomplicated repair and replacement of components.

The detailed analysis done with GSA and its good agreement with analytical calculations give confidence in the design, and the experimental results give decent backing to this confidence, although further tests are necessary. It is hoped that the results of this project will be further developed and incorporated into a shelter that aids displaced peoples someday soon.

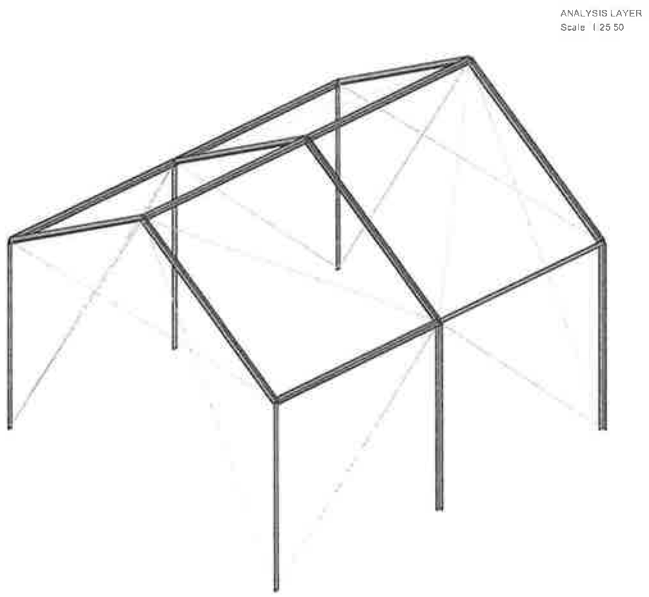


Figure 30: Isometric View of Designed
Frame (rendered in GSA)

6.1 Specification

Component List:

- 18 x 40x40x4mm Equal Angle Aluminium Section
- 18 x M6 Steel Bolt
- 18 x 6mm Wingnut
- 8 x 2.7m length 4mm steel cable
- 6 x 3.4m length 4mm steel cable
- 14 x 4mm cable tensioner

Material Cost of Frame: $140 (estimated from [9])

Weight of Frame: 31.23 kg

Covered Area: 13 m^2

Head Height: 1.8m at side, 2.8m in centre

7. CONCLUSIONS

- If aluminium angles are to be used to carry the given load in a reasonably simple design, the 40x40x4 section is the minimum required to safely do so.
- The frame is easily repairable as it uses only angle sections, cable, nuts and bolts, all of which can be found in developing world workshops.
- The simplicity of the frame allows greater flexibility in procurement which serves to lower price and increase options available to aid agencies.
- The design of the tent is sufficiently simple that a team of six should be able to erect it within half an hour.
- The experimental results and GSA results did not agree well because there were differences in support conditions, joint assumptions and cable connections. It is likely that the GSA results are conservative and therefore can be used to backup the design, but further experiments are necessary to confirm this.
- The frame requires further testing before it is fit for field use. In particular a full sized prototype should be made, investigations done into buffeting effects and the support conditions.

8. FURTHER WORK

There is need for more analysis and testing of this design before it can be safely used in the field. The effects of dynamic wind loading need to be investigated, especially their impact on the covering. The connection of the covering to the frame needs to be designed such that the wind and snow pressures on it are transferred directly to the adjacent members. This is especially true at the supports, as the pockets in the covering here are a vital component of the anchoring system. A full scale model of the frame needs to be built to ensure the joint layout is viable and that the frame is indeed easy to manufacture and construct. This model should be tested in extreme conditions to ensure the analysis that has been done is correct, and that no unconsidered effects cause the tent to become unsafe.

9. PROJECT TIMELINE

2006

June	Initial meeting with ShelterCentre Oxfam Shelter Event
August	Visit to ShelterCentre summer office
October	Literature Review Plastic Analysis of One-Plate Joint Plastic Analysis of Two-Plate Joint Construction of Cardboard Models
November	Creation of CAD Models First Joint Prototype ShelterMeeting in Geneva Second Joint Prototype
December	Pakistan Trip

2007

January	Analysis of Pakistan Data GSA Modelling of Unbraced Model
February	Unbraced Design Checks GSA Modelling of Braced Model Braced Design Checks Switch to Braced Model
March	Design of End-bracing ULS Checks: Derivation of Moment Interaction & Euler Curves
April	Joint Detailing Construction Drawings
May	Model Construction & Testing

10. REFERENCES

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