Analysis of a Reciprocal Roof Framed Shelter for Use in Humanitarian Emergencies

A project submitted in part fulfilment of the requirements for the degree of

Bachelor of Civil Engineering

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Abstract

The primary objective of this project is to practically and theoretically analyse the 'ReciproBoo' reciprocal roof framed shelter and to make recommendations on any areas which could be improved. The project looks to assess whether or not the ReciproBoo shelter and indeed the concept of the reciprocal frame is a viable option for distribution in humanitarian emergencies.

To assess the structural stability of the frame it was necessary to carry out tensile testing on the various consisting components. The values obtained from the materials testing were then used in the computational analysis (Autodesk Robot) of the structure to determine the loading conditions under which it failed. The frame was modified using the computer programme in order to investigate whether or not improvements could be made. These modifications consisted of changes to material type, material thickness, cross sectional shape and the addition of extra components. A practical inspection of the structure was also carried out to identify any problems in the assembly or the general make-up of the frame.

The main findings of the project were that changing the thickness of the structural components, replacing the steel poles with bamboo and replacing side ropes with rods can all result in significant increases in the strength of the structure. It was also found that changing the pitch of the structure would not result in any significant change in the load bearing capabilities of the structure. A similar result was obtained when the bottom rope was changed to a steel rod. Another interesting result was that square section poles were weaker than tubular section poles of the same cross sectional area.

The main conclusions from this project were that the ReciproBoo shelter kit is most definitely a suitable type of shelter for use in humanitarian emergencies. The load bearing capabilities of the frame are suitable while the reciprocal shape enables the frame to evenly distribute surface loads. Although there is scope for modification to the frame, the shelter has a host of benefits making it very well adapted to suit such emergencies. It is felt that it is of great importance that aid agencies worldwide consider the advantages of the ReciproBoo shelter kit and indeed the concept behind the shelter.

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1 Introduction

1.1 Background

As global climate change becomes an ever increasing issue in the modern day the number of natural disasters occurring annually is on the increase leaving millions of people displaced every year. As a result there is an ever increasing demand for emergency relief for these displaced people, one of the primary needs being a roof over their heads. Many of the world's international relief agencies provide tents and tarpaulins for displaced families, however, there is a growing need for a standard frame which can be distributed quickly, in huge quantities, manufactured cheaply and assembled easily in emergency situations. This project focuses on the concept of a reciprocal roof framed shelter which can fulfil all of these needs for use in humanitarian emergencies.

It was through Engineers Without Borders, a non-profit organisation whose aim is to provide young engineers with the opportunity to carry out research and work experience in the field of humanitarian relief, that we first encountered the ReciproBoo concept.

The ReciproBoo frame is a reciprocal roof framed shelter for use in humanitarian emergencies. The idea behind the ReciproBoo is that it uses a small number of members to provide a strong, light weight frame, which is easy to transport in bulk, cheap to manufacture and simple to erect.

Figure 1; The ReciproBoo shelter (www.reciproboo.org)

The ReciproBoo frame has been developed by Shaun Halbert, a veterinarian from the U.K. who has extensive experience working in emergency relief situations. It was during his work that Shaun discovered the need for a standard frame, as part of a shelter kit, which could be distributed quickly and efficiently to disaster situations all over the world. He has developed the ReciproBoo shelter kit over the past number of years in the hope that some of the major international relief agencies will take the concept on board.

1.2 Aims and Objectives

The main component of this project involves the structural analysis of the frame using a combination of materials testing and computational analysis. Our aim is to assess the strength of the frame under various loads and to investigate whether or not improvements can be made to the structure by varying section sizes, section types and even by using different materials within the computer model. Primarily we hope to increase the strength of the ReciproBoo while still maintaining a low cost, light weight, and easily assembled frame.

This report aims to highlight the advantages of the ReciproBoo shelter kit and how the frame itself and indeed the concept of the frame could be used in many of the world's disaster situations regardless of terrain or climate, an area where other relief tents have failings.

The overall objective is to carry out some much needed research work on the ReciproBoo shelter kit. This research can then support the product which will ultimately increase its recognition from some of the larger humanitarian relief agencies.

From a personal point of view we hope to fulfil some of our own aims and objectives including the following;

- To gain an understanding of computational analysis.
- To improve on our knowledge of structural analysis.
- To gain our first taste of research work which may be of benefit in future thesis work.
- To improve on our knowledge of the humanitarian sector, an area where civil engineers can make huge contributions.
- To improve on our document and report writing skills which are very important for engineers in the modern day.

2 Literature Review

2.1 Humanitarian Emergencies

The number of people affected by humanitarian emergencies worldwide has risen dramatically over the past number of years. This is due to an ever increasing global population along with a number of large scale disasters augmented by climate change. The 'number of people of concern' to the United Nations in the year 2000 came to a total of just over 21 million people (UNHCR Global Report 2000). In the year 2010 the total population of concern to the U.N totalled almost 34 million (UNHCR Global Report 2010). As a result of this increase in affected persons, there has been a significant rise in global demand for emergency humanitarian relief along with viable solutions to some of the major issues which obstruct humanitarian and disaster response.

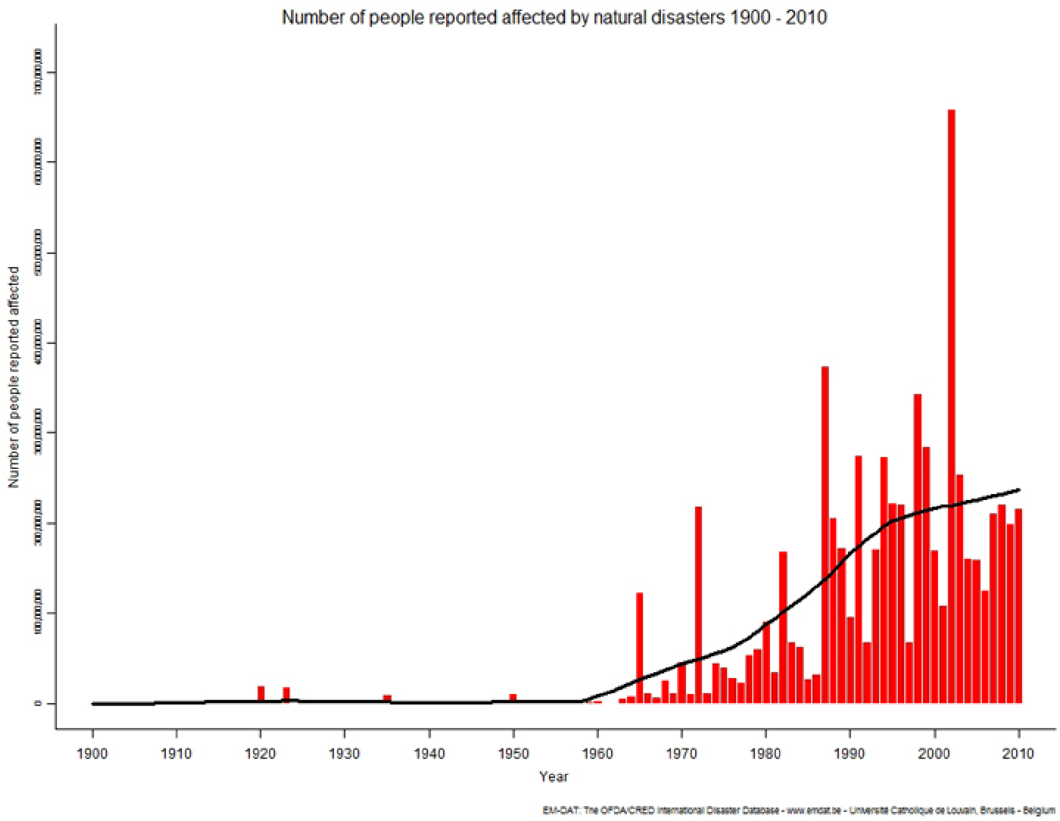


Figure 2; Number of people reported affected by natural disasters 1900-2010 (International Disasters Database)

The primary concerns that need to be addressed during humanitarian relief efforts include healthcare, food, shelter, sanitation and clean water, however in a large scale humanitarian disaster it can be very difficult to ensure that all of the persons affected have been provided with these basic human rights. This is due to a host of obstacles which vary with every situation but which must be overcome to ensure that effective aid is provided. As this report focuses on the analysis of a shelter for distribution in this type of situation, we shall look at some of the obstacles which must be overcome in the distribution of emergency shelters in humanitarian emergencies. It should be noted that some of these issues apply to aid distribution in general. A number of examples from past disaster situations shall be used to show how these obstacles can seriously hamper relief efforts.

2.1.1 Logistics

Logistics is a very important factor in determining the timeframe within which the delivery of an emergency shelter or indeed any type of emergency aid reaches a particular location. In January 2010 during the immediate aftermath of the Haitian earthquake, international relief organisations encountered serious logistical issues. The quake caused detrimental damage to the infrastructure of the country reducing buildings to rubble which filled the streets, destroying the countries sea port and causing the closure of the international airport (IFRC Annual report 2010). The country was left incapacitated as a result. The 2010 floods in Pakistan caused similar logistical nightmares. The huge flood waters swept roads and bridges away leaving it extremely difficult to travel around the country and distribute aid to people in need (IFRC Annual Report 2010).

Figure 3; A Port-au-Prince Street after the Haitian earthquake. (www.telegraph.co.uk)

2.1.2 Cost

Considerable financial resources are required to distribute emergency shelters to humanitarian emergencies. It is therefore essential that adequate consideration is given regarding the selection of the type of shelter for distribution. A case of poor relief shelter selection took place in Northern Mozambique in the year 2001. Relief tents were supplied at a price of US$500 each to approximately 1500 refugees who had been relocated from a camp in the capital city Maputo. However, it was found that within a period of 2 months almost all of the refugees had moved out of the tents due to the intense heat and constructed their own shelters from locally sourced materials (Manfield et al. 2004). It is important to ensure that finances are not wasted and to ensure that maximum efficiency in shelter distribution is achieved.

2.1.3 Terrain

Rough terrain can cause delays in emergency shelter construction in a number of ways. The landscape can cause logistical issues as it may only be possible to travel to certain villages on foot. This can cause serious delays in distributing shelters and indeed aid to the area where they are required. The landscape can also cause issues in the erection of relief shelters. Hilly or mountainous terrain can result in difficulties in locating settlements for displaced people.

2.1.4 Number of people in need

In recent times some of the largest natural disasters have left relief agencies overwhelmed by the sheer number of people in need of humanitarian assistance (e.g. Haitian Earthquake 2010 and the Indian Ocean Tsunami 2004).

2.1.5 Other issues

Other issues which can hamper relief efforts and shelter distribution include war and climate. The war in Afghanistan resulted in an extremely volatile situation leaving it difficult for aid workers to travel to certain areas. Climate can also affect shelter and aid distribution. For example, hurricane seasons are seen in countries such as Haiti while severe cold weather can be encountered in parts of Pakistan and Afghanistan. Heavy monsoon floods must be dealt with in south East Asia. These are some of the areas which have received aid in the past number of years and many more climatic events are encountered annually by humanitarian relief agencies.

There are many more issues which must be contended with in the planning and distribution of emergency relief shelters. ‘Shelter is not only about physical structures, but also the full range of legal, economic and social elements that need to come together to produce a long-term solution that is acceptable to the local community’(IFRC Annual Report 2010).

As a result of the issues discussed above it is very important that relief agencies and engineers alike continue to develop emergency relief shelters to increase performance in all types of situation. This is particularly important in varying climatic conditions. It should be noted that the original design of the 19th century standard military style tents used by agencies such as the U.N and the Red Cross has changed very little (Manfield et al. 2004).

Figure 4; An example of standard tents used by the IFRC, the UN and the ICRC (IFRC)

2.2 The 'ReciproBoo' Reciprocal Roof Frame Shelter

The 'ReciproBoo' reciprocal roof frame shelter is a shelter type which has been developed for use in humanitarian emergencies all over the world. The simple design has a range of key features which make it suitable for use in a variety of situations. The frame is similar to a tent structure in that it consists of structural rods, side ropes and guy ropes however the main difference between the two is that it consists of four poles tied together to form a reciprocal shape which is then supported by two upright components as can be seen below.

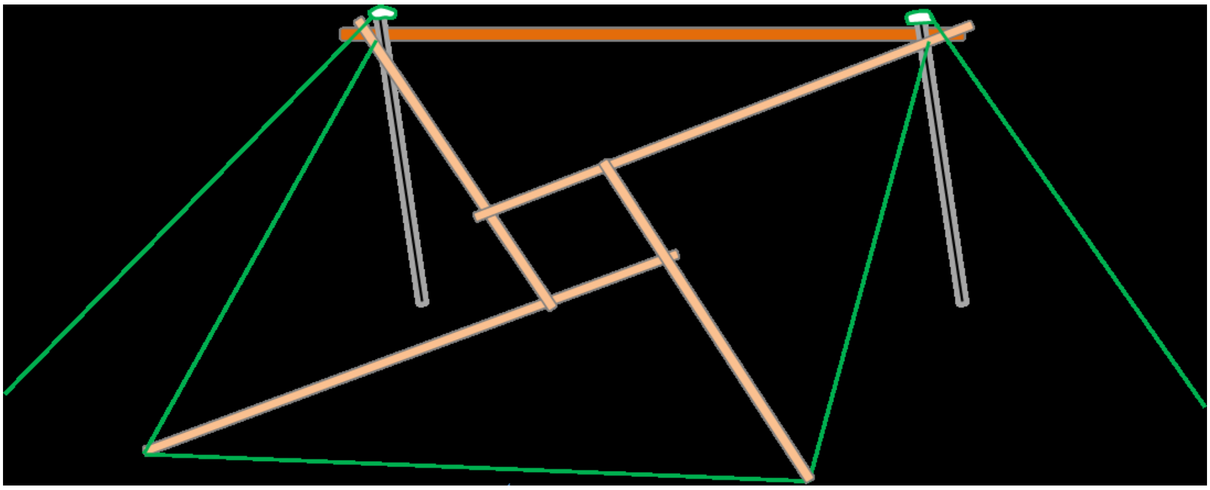


Figure 5; ReciproBoo frame (www.ReciproBoo.org)

2.2.1 The Concept

The frame itself was designed by Shaun Halbert a veterinarian from the United Kingdom with extensive experience working in disaster situations around the globe. While working in these humanitarian emergencies Shaun realised that there was a great need for a standard, low cost relief shelter that aid agencies could distribute in the form of a shelter kit. This could be used as an alternative to the thousands of tarpaulins that are distributed every year without frames. The ReciproBoo shelter kit is low cost, easy to transport, easy to assemble and highly effective in providing adequate shelter. The idea behind the ReciproBoo shelter kit is that it will provide emergency shelter for people in need. It will also provide them with a footing from which they can commence rebuilding their homes.

2.2.2 Situations in which the ReciproBoo can be used

Disaster situations can have many variations depending on climate, location and political climate. The ReciproBoo kit can prove very useful in a variety of these situations. The reciprocal shape of the frame enables it to support materials with insulating qualities making it suitable for both cold and warm climates while the light weight frame can be easily assembled and disassembled making it easy to carry and to transport. As a result the ReciproBoo is suitable for people displaced by natural disasters or refugees who cannot stay in one location for a long period of time, a problem faced in many war torn countries.

2.2.3 The need for a shelter of this kind

In many humanitarian emergencies the immediate reaction of aid agencies is to distribute thousands of relief tents to the displaced population without hesitation. However, the cost of distributing this large amount of tents can be colossal with some costing in the region of hundreds of euro. It should be noted that 'it is acknowledged that shelter using local materials and construction techniques is, in nearly all circumstances, the preferred solution to the shelter requirements of displaced people' (Manfield et al. 2004). This is understandable as local construction techniques in many areas have been developed over thousands of years to suit the surrounding environment. It is therefore very important that relief agencies do not invest unnecessary resources into supplying expensive relief tents designed for long term usage when 'other shelter solutions and other settlement options could be implemented in preference to tents without impacting significantly upon the short-term health and security risks borne by displaced persons' (Manfield et al. 2004).

It is, however, understandable that aid agencies may not have the time to assess whether or not standard relief tents are viable in times of great urgency. It is vital that displaced populations are supplied with immediate short term shelter in the aftermath of a large scale disaster or in fact in any humanitarian emergency. This is where the ReciproBoo shelter kit has major benefits.

The ReciproBoo shelter, although smaller than a standard relief tent is much cheaper and much more adaptable to suit its surrounding environment. The fact that the frame can be disassembled into a small package means that it can be distributed in huge numbers allowing aid agencies to provide immediate and adequate shelter to masses of people at a very low financial cost. The ReciproBoo shelter kit is ideal for immediate distribution in disaster situations as it can give aid agencies the opportunity to assess whether or not more permanent structures will be needed. In some areas it is likely that many of the displaced population will rebuild their own homes using locally sourced materials and techniques.

There is also a great need for a shelter of this kind for people on the move such as refugees fleeing conflict areas. The standard relief tent is much too heavy to carry over long distances and a considerable amount of time and skill can be needed to assemble the frame. The ReciproBoo shelter is much lighter and easier to carry and can be assembled in a matter of minutes.

Figure 6; Refugees in the Congo.(www.rnw.nl)

Another reason to consider the need for this shelter is the huge number of tarpaulins distributed to humanitarian emergencies every year without a supporting frame. Without a solid frame it is very difficult for the beneficiary to lay any kind of insulating material onto the tarpaulin making it very uncomfortable and sometimes unbearable underneath. The ReciproBoo frame, due to its low cost, could easily be distributed as a standard frame to go with the thousands of tarpaulins distributed each year.

Figure 7; A shelter in post earthquake Haiti made from old bed sheets. A tarpaulin and frame could provide much more comfort and security than this type of shelter.(Photograph by Shaun Halbert)

2.2.4 Key Components

At present the ReciproBoo kit consists of the following components;

- 20 interlocking steel poles (22mm diameter, 900mm length)
- Sisal twine
- Polypropylene rope
- 2 tarpaulins
- 4 steel hooks
- 4 steel pegs

Figure 8; Components of the ReciproBoo frame (www.ReciproBoo.org)

2.2.5 Dimensions

When fully erected the highest point within the frame is approximately 1.8m depending on the pitch at which it is set. The Length of the floor area within the frame is 4.5m while the width is 3.4m. The total floor area provided after guy ropes and tarpaulins are fully secured is 17n

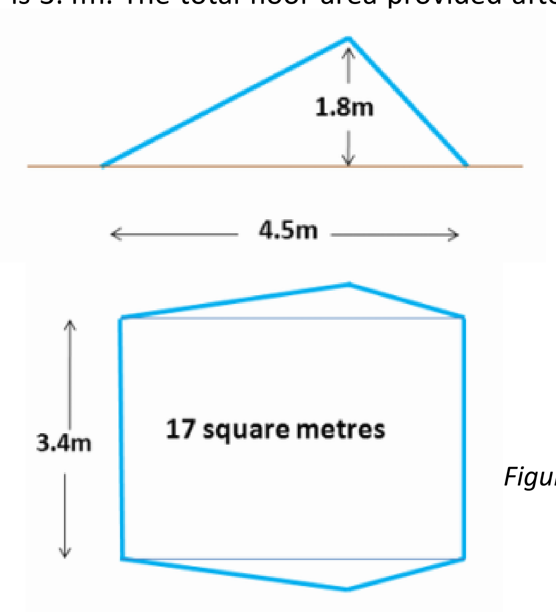


Figure 9; Frame dimensions

2.2.6 Assembly

The assembly of the frame is a very simple procedure and this is one of the key advantages that the ReciproBoo holds over relief tents. The following steps give a summary of the assembly procedure.

Step 1:

- Attach two lengths of rod to each of the four poles with a red end.
- Overlap these poles as shown in figure 10 below and cross lash the joints using the sisal twine provided.

Figure 10; Layout and cross lashing of joints.

Step 2:

- Assemble the ridge pole using four sections of rod.
- Place the frame on top of the ridge pole and cross lash at the joints as shown in figure 11 below.
- Insert a hook into each of the open ends of the frame rods and use these hooks to tie the side ropes. (figure 11 below)

Figure 11; Ridge pole, frame and side ropes (left) and side ropes tied to hooks (right).

Step 3:

- Insert a hook into the open end of two of the unused rods as shown in figure 12 below. These rods will act as the support components.
- Place these support rods at either end of the ridge pole and sit the ridge pole onto the hooks (figure 12).
- Cross lash the joints using the sisal twine
- Insert each of the last two rods into the bottom end of both upright rods to form the fully elevated structure.

Figure 12; Hook in the open end of the supporting rod (left) and fully elevated frame (right).

Step 4:

- Attach the end tarpaulin to one end of the frame and fold over the frame as shown in figure 13 below.
- Lift the main tarpaulin over the ridge pole as shown in figure 13 and tie it securely to the frame.
- Attach the guy ropes to the top of each of the support poles and fix to the ground using hooks to finalise the ReciproBoo assembly as shown below in figure 13.

Figure 13; End wall tarpaulin attached and folded over (left) and completed assembly (right).

2.3 Variations of the ReciproBoo

The ReciproBoo and indeed the concept of the reciprocal roof frame can be used in a variety of ways depending on the situation and the needs of the people that it is being supplied to. The frame itself is very adaptable and can be modified to suit these varying situations. Some of the variations of the frame are described below.

2.3.1 Storm Mode

Many of the world's humanitarian emergencies occur in areas where heavy storms are commonplace and as a result the ReciproBoo frame has been designed to withstand heavy winds. The frame can be adjusted to 'storm mode' by removing one pole from each of the two supporting poles thus lowering the entire frame to a pitch which provides less of a surface area for heavy winds to catch. The removed poles can then be used to provide additional support to the ridge pole if necessary. This simple adjustment can be carried out in a number of minutes.

Figure 14; Storm mode. (www.ReciproBoo.org)

2.3.2 Elevated Frame

The bottom of the reciprocal frame can be elevated to provide greater space within the tent. For example, the base can be secured to a wall as shown in figure 15 below or to any securely fixed prop.

Figure 15; Elevated frame. (www.ReciproBoo.org)

2.3.3 Transitional Roof

The ReciproBoo can be used as a transitional roof frame for buildings which have severe roof damage. This transitional roof can be used to replace the badly damaged roof and provide a family with shelter from the elements in their own home until a more permanent solution has been decided on. The transitional roof consists of fixing two (or possibly more) of the reciprocal elements of the frame to each other to form a larger span. This concept can apply to both single and double pitch roofs.

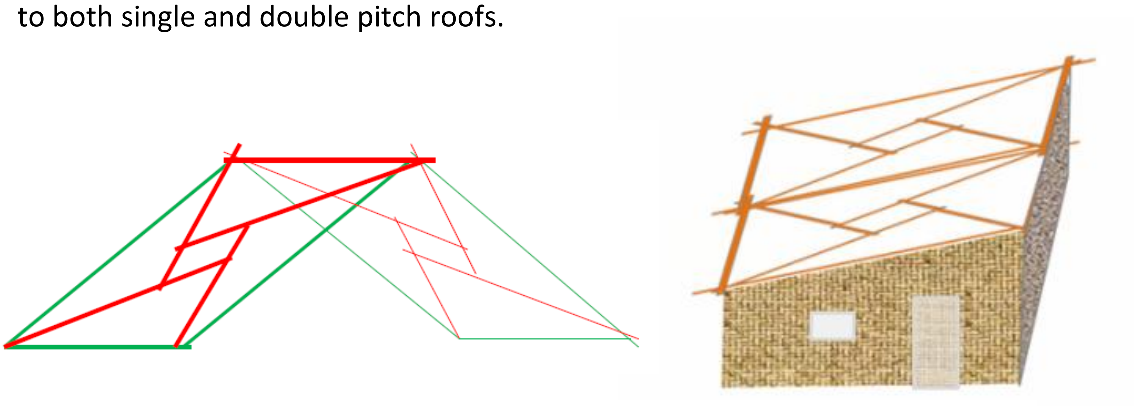


Figure 16; Transitional roof to suit a double pitch and a single pitch roof. (www.ReciproBoo.org)

2.3.4 Bamboo

Bamboo can be found growing in many parts of the world and is used commonly as a construction material due to its rigidity, strength and availability. It can be used to provide additional support to any of the ReciproBoo variations and is even a useful substitute for the steel rods used. Bamboo can also be used to replace the side ropes in the ReciproBoo frame to provide extra strength and stability. Using the concept of the reciprocal frame it is possible, using bamboo, to construct further variations of the ReciproBoo. Such variations include the six component and eight component reciprocal roofs.

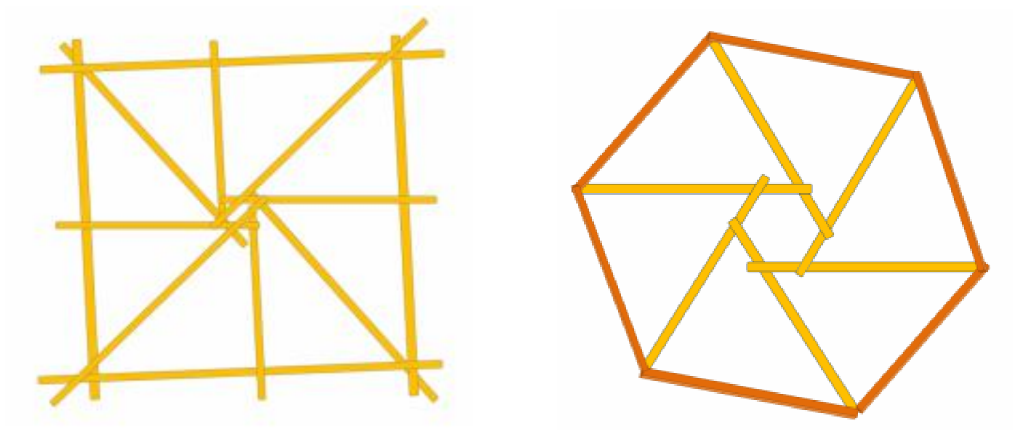


Figure 17; Plan of eight component reciprocal frame and six component reciprocal frame. (www.ReciproBoo.org)

2.4 A Brief History of Reciprocal Frames

It is not known exactly when the first reciprocal frames were designed however the principle of the frame can be traced as far back as ancient times in dwellings such as Indian tepees and Eskimo tents (Popovic, 1996). The reciprocal concept would have proved useful when materials were in short supply as it enables a span to be crossed even when components are shorter than that span. The concept would have been used in bridges and structures alike.

Over time the concept of the reciprocal roof has evolved into an architectural feature and has been used by architects in the design of modern day buildings around the world. Some of the earlier examples of studies and investigation into the reciprocal frame concept are contained in the work of Villard de Honnecourt (13th century) who sketched a solution for constructing a roof when material spans were too short (Reciprocal Frame Architecture, 2008). Leonardo da Vinci (1452-1519) is also known to have carried out studies into the reciprocal frame concept. His sketch in the Codex Madrid shows a reciprocal frame very similar to that drawn by de Honnecourt (Reciprocal Frame Architecture, 2008). It appears that the true homeland of reciprocal frame architecture is Japan where the concept has been used since the 12th century in the construction of Buddhist temples (Popovic, 1996). However, due to the fact that these reciprocal frame roofs would have been constructed from timber it is very difficult to find any of this ancient architecture in Japan. Many of the roofs have been destroyed by fire or deterioration.

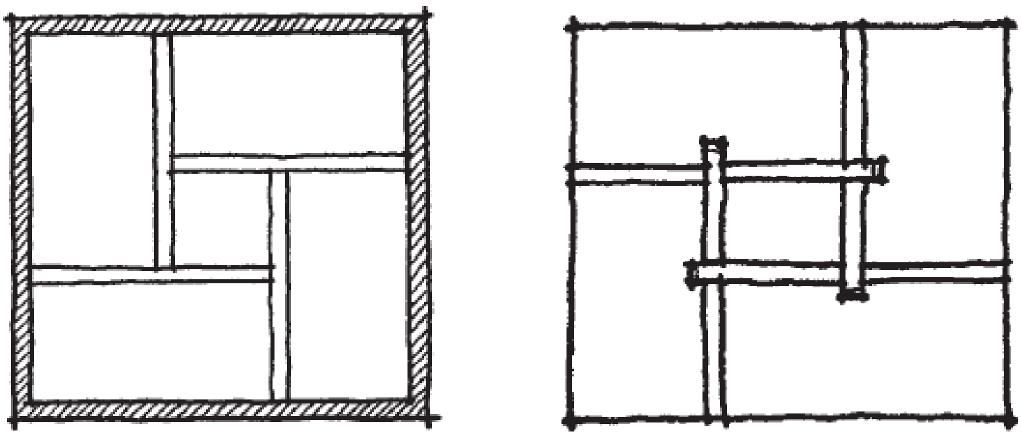


Figure 18; Villard de Honnecourt's sketch (left) and Leonardo Da Vinci's sketch (right). (Reciprocal Frame Architecture, 2008)

A fine example of modern day reciprocal frame architecture can be seen in the Bunraku Puppet Theatre in southern Japan. The theatre, designed by Kazuhiro Ishii, consists of four buildings, three of them are designed with timber reciprocal roofs. Figure 19(left) shows the roof structure in the exhibition hall while figure 19 (top) shows the reciprocal roof structure of the cafe and shop.

Figure 19; Reciprocal frame roof in the exhibition hall (left) and the reciprocal roof frame in the cafe/shop area (top). (Reciprocal Frame Architecture, 2008)

2.5 Influence of Climate and Location on Shelter Design

Location and naturally, the climate, have a huge bearing on the type of emergency shelter that should be provided for families in need. Humanitarian emergencies are common in both cold and warm climates and it is important that aid agencies bear in mind that shelters must be designed to adapt to suit all types of environment. Insulation can be a major problem when it comes to emergency shelters and this applies in both hot and cold climates. Figure 20 below shows a Kenyan family sitting underneath a canopy of bushes which they have built rather than sitting in their tent which has become unbearably hot inside due to a lack of insulation.

Figure 20; Family underneath canopy (photograph by Shaun Halbert).

It is common knowledge that insulation is an important requirement in cold climate emergency shelters however 'agency policy concerning the provision of emergency shelter in cold climates continues to be ambiguous' (Manfield et al. 2004). The 2010 earthquake in Pakistan is a prime example of an emergency situation which required cold weather emergency shelters. As winter 2010 moved in it was necessary for the Pakistan Red Crescent Society and the IFRC to design and distribute a winterised shelter kit to the northern regions of Pakistan to prevent further loss of life (IFRC Annual Report 2010).

The location of a disaster situation also has a bearing on the type of materials that are readily available and can be used to either construct or to provide additional support to emergency shelters. For example, bamboo is common in many areas of the globe and can be very useful as a construction material. Many rural locations have an abundance of reeds and grass which can be used as insulation from either extreme heat or perishing lows. Urban settings can have large amounts of corrugated sheeting in wreckage which also provides good insulation. The U.N Global Appeal 2012-2013 states that ‘shelters in rural areas shall use thatch while shelters in urban areas shall use iron sheeting’ as it highlights ambitions to construct 15,000 shelters for families returning to South Sudan. Figure 21 below is an example of reeds and vegetation being used as insulation on a Bolivian shelter.

Figure 21; Vegetation covering a shelter (photograph by Shaun Halbert).

Another factor which must be taken into account when designing or selecting a relief shelter for distribution is the loads that are likely to be imposed on the structure as a result of the climate and location. Weather loadings such as snow and wind may be imposed on a frame in a cold climate while heavy rains and high winds may be imposed on a shelter in a tropical climate. Similarly shelters should be able to support the galvanised sheeting that may be used as insulation in cold or urban environments while loads in the form of reeds and vegetation must be supported in warm or rural locations.

2.6 Benefits of the ReciproBoo Frame

2.6.1 Cost

The small number of members in the ReciproBoo frame and the easily manufactured steel poles lead to a price of $45 (€34) for the manufacture of each frame. This is approximately one sixth the cost of other standard relief tents used in humanitarian emergencies. The small number of steel poles has also resulted in an extremely low weight of the combined structure and this along with the ability to pack the disassembled frame into a small package will result in very low transport costs. Large quantities of the ReciproBoo kit may be distributed in one journey due to the weight and size of the kit saving costs on travel to and from depots. The low cost of the frame allows aid agencies to distribute more shelters to more people in need.

2.6.2 Quick Assembly

The simple make up of the frame enables even unskilled workers to assemble the shelter in a very short period of time. It may even be possible for one person to assemble the frame alone. Spring loaded buttons are located at the end of each rod allowing rapid make-up of longer components. The ability to easily assemble the frame means that families do not have to wait for engineers to assemble shelters for them. The kit can simply be given to the family for them to assemble the frame for themselves ensuring that people are not left for a further period of time without shelter.

2.6.3 Adaptability

Adaptability is arguably the greatest benefit of the ReciproBoo frame and indeed the concept of the reciprocal frame. Adaptations can be made to the frame in the form of changes to structural materials, layout changes and the addition of components using local materials.

Adaptations can be made to the frame by using materials such as bamboo to replace the steel rods while alternative materials can also be used to cross lash joints. A prime example of the adaptability of the ReciproBoo and the reciprocal frame concept is Medair's recent application for the funding of 11,000 bamboo shelters for use in southern Sudan based on the reciprocal frame concept (www.ReciproBoo.org). The frame dimensions were modified slightly by Medair to suit the height of Sudanese nationals and it was decided that strips of rubber from old tyre tubes shall be used to cross lash the joints.

Additional supporting members can be used to provide further strength to the structure. Locally found materials can be used to replace side ropes and provide extra strength and stability while a ‘fork shaped’ branch can be used to provide additional support to the ridge pole. The use of local materials is also crucial in the provision of insulation on the structure.

Another addition is that the frame can be adapted to suit different types of terrain. The shelter can be easily erected on slopes and uneven ground without any major structural changes.

The ReciproBoo shelter enables the beneficiary to utilize their own resourcefulness and whatever materials they can find to improve it.

2.6.4 Transport

The weight of the frame and the ability to pack the kit into a small compact package makes it very easy to transport. As stated before, this has many economic benefits however it is important to note that this is a very important factor for some beneficiaries. Many refugees in war torn countries are forced to move themselves and their families to new locations on a regular basis and the ability to carry the shelter kit with them is very important.

3 Materials and Methods

3.1 Materials Testing/Properties

Before modelling the frame in Autodesk Robot it was necessary to first carry out tests on the materials used in the construction of the frame in order to determine the geometrical and mechanical properties of the materials. These material properties were required in order to be able to create the specific material used in the frame in Autodesk Robot. Tests were carried out on the steel rods used to create the reciprocal frame and the two types of ropes used to increase the strength of the structure. The properties required in order to carry out the analysis in Autodesk Robot are:

- Diameter
- Thickness
- Cross-sectional area
- Young's Modulus, E
- Shear Modulus, G
- Poisson's Ratio, ν
- Density, ρ
- Max Tensile Strength
- Yield Strength

3.1.1 Steel Rod Testing

Several samples of steel rods used in the construction of the frame were taken and measured to check the internal and external diameters of the rods. Measurements were taken using a Vernier callipers and an average reading was calculated. As can be seen from Table 1 the average external diameter of the rods is 22.087mm and the average internal diameter is 20.20mm. The cross sectional area is 65.97mm^2.

Geometrical Properties - Steel Rods					
	Sample 1	Sample 2	Sample 3		Average
External Diameter (mm)	22.2	22.06	22		22.087
Internal Diameter (mm)	20.3	20.25	20.05		20.20

Table 1; Geometrical Properties - Steel Rods

Young's modulus, maximum tensile strength and yield strength were obtained by carrying out tensile tests on rod samples. Ideally it would have been preferable to carry out the tensile tests on a large number of samples and get average values for each of the properties. However, only one sample rod was provided which could be tested until destruction. The values for shear modulus (G), Poisson's ratio (ν) and density (ρ) were obtained from the programme CES Edupack. This is a computer programme which contains properties of a range of different materials used in engineering.

The testing procedure for the rods was relatively simple. The rod was cut in two so that two tests could be carried out. Metal inserts were made up for the ends of the samples so that clamping would not cause the rods to become damaged or crushed and thus affect the results. The sample was inserted into the testing machine. The rod was then loaded in tension until failure. The results were automatically plotted on a stress v strain graph by the machine. Average values were taken for these results and are shown in Table 2.

Mechanical Properties - Steel Rods				
	Test 1	Test 2		Average
Area (mm^2)	65.97	65.97		65.97
Max Loading (kN)	28.18	27.17		27.675
Ultimate Tensile Strength (N/mm^2)	427	412		419.5
Yield Strength (N/mm^2)	408	404		406
Young's Modulus, E (kN/mm^2)	162	147		155
Shear Modulus, G (N/mm^2)	-	-		80000
Poisson's Ratio, ν	-	-		0.3
Density, ρ (kg/m^3)	-	-		7750

Table 2; Mechanical Properties - Steel Rods

The below graph contains a plot of stress versus strain for the tensile tests carried out.

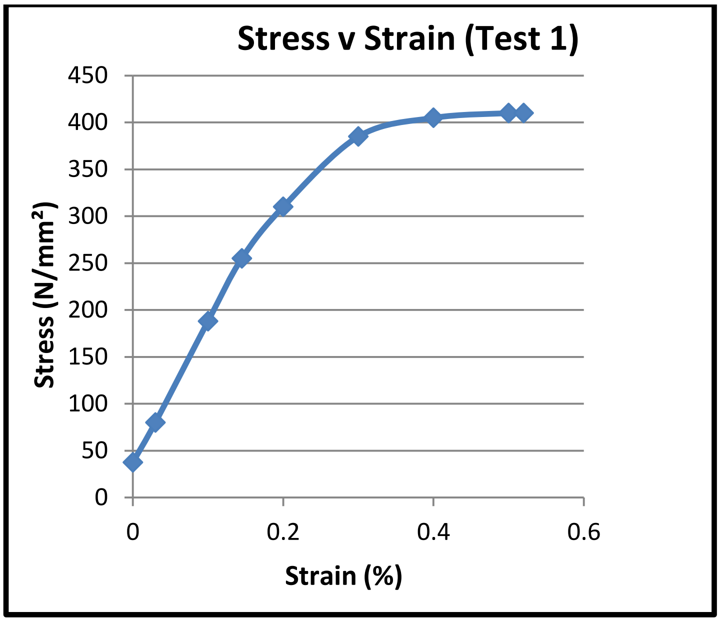


Figure 22; Stress v Strain graph of results from rod tensile test

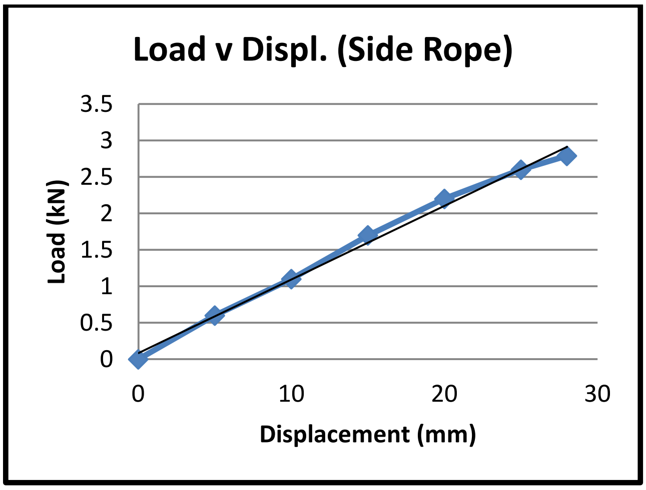
Figure 23; Tensile Testing Machine

3.1.2 Rope Testing

Similar tests were also carried out on the guy ropes and side ropes used to add support to the structure. Samples of both ropes were clamped into the same machine used in the rod testing and the ropes were loaded in tension until failure. This provided values for Young's Modulus and the tensile strength of the ropes. The results were automatically plotted on a stress v strain graph by the machine. Table 3 below shows the results obtained. The values for Poisson's ratio and density were again obtained from the programme CES Edupack. The value for Shear modulus was calculated using the relationship: $G = \frac{E}{2(1+\nu)}$.

Geometrical & Mechanical Properties - Ropes		
	Side Ropes	Guy Ropes
Diameter (mm)	7	4
Area (mm^2)	38.4846	12.5664
Failure Load, kN	2.79	1.29
Tensile Strength (N/mm^2)	72.50	102.65
Young's Modulus, E (kN/mm^2)	1.009	0.317
Poisson's Ratio, v	0.42	0.42
Shear Modulus, G (N/mm^2)	355.28	111.62
Density, ρ (kg/m^3)	900	900

Table 3; Geometrical & Mechanical Properties – Ropes



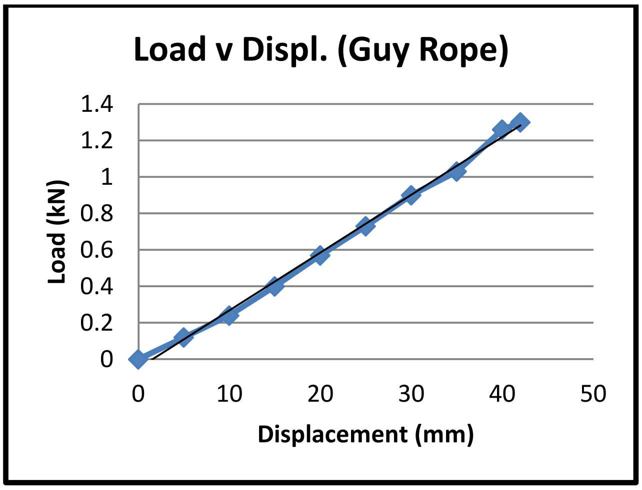


Figure 24; Load v Displacement - Side Ropes & Guy Ropes

It can be seen from the above graphs that the displacement in the ropes increases linearly with applied load until the material fails. Unlike the steel rods tested previously there is no plastic deformation prior to failure.

3.1.3 Bamboo

Bamboo is a very suitable material for possible use in the building of this frame as it is a light, flexible and strong material. However it is very difficult to define specific properties for the material as there is a range of over 500 species of bamboo all of which will have slightly different attributes. In order to create a model of the frame using bamboo in Autodesk Robot it was necessary to take an average value for the bamboo properties provided in CES Edupack. It is worth noting that bamboo strength is largely dependent on age and moisture content. Table 4 contains the properties used in modelling the bamboo frame.

Bamboo Properties		
	Range	Value Used
Density, ρ (kg/m^3)	600-800	700
Young's Modulus, E (kN/mm^2)	15-20	17.5
Shear Modulus, G (N/mm^2)	1.21-1.36	1.285
Poisson's Ratio, v	0.32-0.46	0.39
Yield Strength (N/mm^2)	35.9-43.9	39.9
Tensile Strength (N/mm^2)	160-320	240

Table 4; Bamboo Properties

3.2 Building the Frame

A sample frame was obtained and built in order to bring to light any practical issues associated with the construction of the frame and the materials used. Due to the fact that the frame could not be tested until destruction as it was needed for demonstration purposes meant that there were certain limitations to the extent of information that could be gathered from a practical point of view. However building the frame was a very worthwhile exercise as it indicated certain areas which needed to be focused on while analysing the structure in Autodesk Robot.

The speed and ease at which the frame could be constructed was very impressive. The main advantages observed while building the frame are outlined below.

Advantages:

- Speed and ease of construction
- Can be assembled by one person
- All poles are interchangeable so there is no confusion as to which member goes where
- Frame can easily be lowered and elevated depending on wind conditions, terrain and space required
- Frame is extremely lightweight making it easily transportable
- Easily repairable

However concerns arose with other aspects of the structure which need to be addressed in order to get the maximum performance out of the frame. There were significant deflections and deformations in the frame when minimal loads were applied to different parts of the structure, in particular the ridge pole and where members crossed to form the reciprocal part of the frame. The main reasons for such deformations were due to the interlocking connections between members not being rigid enough and also the fact that the material used is so light.

When the members are connected together there is a significant amount of rotation present due to the connections being too loose when ideally the connection should be fully rigid allowing no rotation between members. If the connections between the interlocking members were fully rigid there would be much less deformation in the structure and this would add significantly to its strength. Therefore sourcing members which can be connected rigidly without any slack in the connections needs to be seriously considered in order to maximise the potential of the frame.

Another area of concern highlighted during the construction of the frame is the tying of the cross-lashed joints. During our assembly of the frame there was no difficulty in the tying of the joints and we found the strength of the cross-lashing very impressive. However the strength of the joints is dependent on the person tying the joint and his/her physical capabilities. Obviously in an emergency situation the people tying the joints could possibly be injured, weak or ill leading to a likelihood of a range of different strengths of joints. If the cross-lashing was tied to a poor standard it would result in the joints been very loose and would allow rotation between members in the frame thus reducing the strength and rigidity of the entire structure. Also there is a strong likelihood that the joints will slip during time as there is very little friction between the sisal twine used to tie the joints and the pole members. Obviously, loading and poor standard of cross-lashing will accelerate the joints slipping. At the same time however, it is worth noting that in such an event it would be possible to repair the joints by undoing the cross-lashing, restructuring the members and then re-doing the cross-lashing. This process would require very little effort and could be done in a matter of minutes.

Performance of the cross-lashed joints could be increased by using square members instead of tubular members. Tying of the joints would be made easier due to the flat surfaces of the material fitting together better making it easier to hold the members when starting the tying of the joint as they would not slide against each other as much as tubular members. There would also be more friction between the members in the joint which would possibly reduce the likelihood of the joint slipping over time.

Advantages could also be gained from replacing the side ropes with steel members and/or adding an extra vertical member to support the ridge pole. This would add extra strength and rigidity to the structure but at the same time would increase the overall weight of the frame. It is worthwhile analysing the structure in Autodesk Robot with these additions to test whether the increase in weight of the frame is overshadowed by the increase in the strength caused by the addition of extra members.

Overall, building the frame was a very worthwhile exercise as it highlighted particular areas which need to be focused on when carrying out the analysis in Autodesk Robot.

3.3 Analysis of the Structure

The aim of this section of the project is to analyse the structure in a 3D structural analysis package in order to identify the location and magnitude of stresses and deformations in the structure. This will highlight the area's most susceptible to failure in the frame. The analysis is focused on varying the following properties in the structure in order to give advice on changes which will improve the strength of the frame.

- Material thickness – It was clear from building the frame that the tubes used are very light and therefore increasing the material thickness by a small amount could enhance the strength of the frame significantly.
- Member sections – The frame is analysed using both tubular sections and square sections.
- Pitch – As the frame is likely to be used at a range of different pitches the variations in strength depending on pitch is analysed.
- Extra members – The effects of replacing the side ropes with steel members and adding in an extra vertical member to support the ridge pole is analysed.
- Material Type – The structure is analysed using the material properties obtained from the lab testing but also using the bamboo properties obtained from CES Edupack.

3.3.1 Structural Analysis Package

Originally the plan was to analyse the structure using the structural analysis programme CADS A3D. However the applications of this programme were limited and did not fully suit the type of analysis required for the ReciproBoo frame. The programme could not be used to analyse ropes/cables which are present in the make-up of the frame. Making small changes to the structure of the frame (e.g. pitch, extra members etc.) was also a long and tedious process.

Alternative solutions to this problem considered before finally deciding to use the programme Autodesk Robot. This programme is much more user friendly, changes to the structure can be easily implemented and it can be used to analyse cables/ropes.

3.3.2 Building the Model

In order to build the model of the ReciproBoo frame in Autodesk Robot it was first necessary to create the material type and the section type using the data obtained from the laboratory tests. It was also necessary to make various assumptions regarding the joints in the frame in order to carry out the required analysis. These assumptions are:

- Members are fully fixed at the ground – In order to get the maximum performance out of the structure it is envisaged that the members will be fully fixed at ground level. This can be acquired by building up clay or rocks around the base of the members or by pushing the ends of the poles into the ground.
- Connections between members are rigid – It was discovered from building the frame that there is a small amount of slack in the connections between members. However for the purpose of this analysis it is assumed that the members are rigidly connected.
- Cross-lashed joints are rigid – The performance of the cross-lashed joints is determined by how tight the joint is tied. For this analysis it is assumed that the joints are tied as tight as possible making the joints between members rigid.

Using the above assumptions the frame could be modelled and adjusted to analyse different members, pitches, materials etc.

3.3.3 Theoretical Stress Calculation

In order to have an idea of the general range the stress output from Autodesk Robot should be in, a simple hand calculation is used to determine the theoretical stress in the ridge pole due to it's self-weight. This gives a ball park figure to compare to the stress output given by Autodesk Robot when the model is analysed under its self-weight. This is used to confirm that the structure has been modelled correctly. It is likely that the value output from Autodesk Robot will differ slightly to the theoretical value due to the connections in the members forming the ridge. The formula used to calculate the theoretical stress is, $\sigma_y = \frac{My}{I_y}$, where:

- σ_y is the stress in the outermost fibre in the member.
- M is the bending moment due to the self-weight of the ridge pole. M is calculated by assuming the ridge pole is simply supported at each end meaning the bending moment is, $M=wl^2/8$. Where w is the unit weight of the ridge pole and l is the length of the ridge.
- y is the distance from the centroid of the member to the outermost fibre.(Figure 5)
- I_y is the moment of inertia.

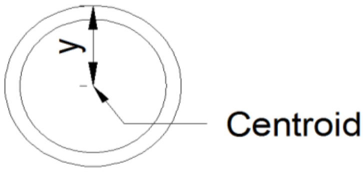


Figure 25; Distance from Centroid

3.3.4 Loading

Depending on the location and type of emergency the frame will be used in there is a large range of load types the frame could be subject to. The frame is likely to be used in different climate types leaving the likelihood of it been subjected to loads from snow wind and other variables. Also it is possible that different materials will be placed on top of the frame to add protection and insulation to the tarpaulin. Materials such as timber, reeds, branches, metal sheeting or any other material available in a disaster situation are likely to be used. Therefore it is necessary to analyse the structure when subject to various combinations of these loads to determine whether or not the frame has the ability to carry these forces without failure. The type and magnitude of loads the structure is analysed under are shown below.

<u>Tarpaulin:</u>

The weight of the tarpaulin supplied with the ReciproBoo kit is 5kg. This translated to a uniformly distributed force of 0.00356kN/m^2.

Wind Loading:

In this analysis it is assumed that the structure will be placed in such a position that the main face of the frame will be facing the wind (Figure 26). It is almost impossible to put a value on the wind loading which the frame is likely to encounter during its use. Therefore the frame will be analysed subject to loading from a 10m/s (≈20mph) wind. This magnitude of wind is likely to occur in most climates around the globe. Calculations for this wind load are shown below.

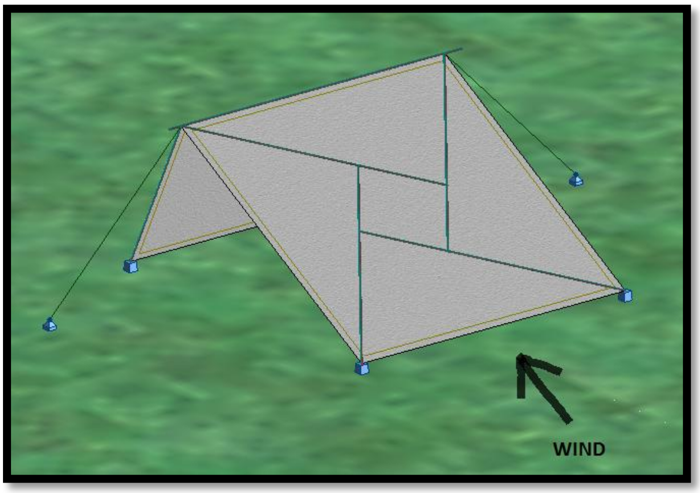


Figure 26; Wind Direction

Table 2. Dynamic pressure q_s (in Pa)

V_e m/s	+ 0	+ 1.0	+ 2.0	+ 3.0	+ 4.0	+ 5.0	+ 6.0	+ 7.0	+ 8.0	+ 9.0
10	61	74	38	104	120	138	157	177	199	221
20	245	270	297	324	353	383	414	447	481	516
30	552	589	628	668	709	751	794	839	885	932
40	981	1030	1080	1130	1190	1240	1300	1350	1410	1470
50	1530	1590	1660	1720	1790	1850	1920	1990	2060	2130
60	2210	2280	2360	2430	2510	2590	2670	2750	2830	2920

* 1 Pa = 1 N/m^2

Table 5; Wind Pressures (BS6399 Part 2)

Wind Loading			
Wind Speed (m/s)	Wind Speed (mph)	Pressure (N/m^2)	Pressure (kN/m^2)
10	22.36	61	0.061

Table 6; Wind Loading Calculations

As can be seen from the above tables a wind speed of 10m/s hitting the frame corresponds to a uniformly distributed force of 0.061kN/m^2. Wind loads are applied normal to the surface of the frame.

<u>Snow Loading:</u>

Snow loading is not a major issue with this structure as it is unsure whether or not the snow will settle on the tarpaulin or just slide off. In the event of heavy snowfall it would be possible to remove the snow from the frame if it were building up to dangerously high levels. This analysis looks at the frame being loaded by 50 mm of snow. The force applied to the frame from the snow is calculated using the fact that snow is approximately one tenth the density of water. Table 7 below shows the relevant calculations.

Snow Loading		
Density (kg/m^3)	Depth (mm)	Load (kN/m^2)
100	50	0.04905

Table 7; Snow Loading Calculations

<u>Corrugated Steel Sheeting:</u>

The frame is likely to be insulated and protected using a range of different materials as mentioned before depending on what is available in the particular situation. As corrugated steel sheeting is probably the heaviest material that may be used this analysis looks at such loading. The force experienced by the frame, taking an average value from a range of weights of corrugated sheeting available from different suppliers, is calculated below.

Steel Sheeting Loading		
Weight (kg/m^2)		Load (kN/m^2)
7		0.06867

Table 8; Steel Sheeting Loading

Table 9 below shows a summary of the loads the frame is analysed under.

Loading Summary	
Source	Load (kN/m^2)
Tarpaulin	0.00336
Wind	0.061
Snow	0.04905
Steel Sheeting	0.06867

Table 9; Loading Summary

3.3.5 Safety Factors

The purpose of safety factors in engineering is to provide a margin for error in design when faced with uncertainty regarding the exact loading a structure will encounter. In general, the factors for safety in structural design are 1.35 for dead loads and 1.5 for live loads. However in the case of this frame there is much less margin for error than for example in designing a multi-storey building. Therefore the factors of safety adopted in analysing the loads on the ReciproBoo frame are much lower. A safety factor of 1.0 has been chosen for dead loads (self-weight and tarpaulin) as the exact loads are known. For live loads (wind, snow, sheeting), a safety factor of 1.1 is used as there is a degree of uncertainty regarding the possible magnitude of these loads likely to be on the frame.

3.3.6 Load Combinations

The analysis of the frame looks at the effects of several combinations of the above loads on the structure. Each combination includes the self-weight of the frame and the weight of the tarpaulin as the frame will always be subject to these loads. The addition of other loads (wind, snow etc.) is varied between different combinations. It is highly unlikely that the structure will be subject to all of the loads at the same time but the effects if such loading did occur is analysed regardless. The different combinations, including the safety factors adopted are listed below.

- Combination 1 – Self-weight + Tarpaulin
- Combination 2 – Self-weight + Tarpaulin + 1.1x Corrugated Steel Sheeting
- Combination 3 – Self-weight + Tarpaulin + 1.1x Wind
- Combination 4 – Self-weight + Tarpaulin + 1.1x Snow

- Combination 5 – Self-weight + Tarpaulin + 1.1x Wind + 1.1x Corrugated Steel Sheeting
- Combination 6 – Self-weight + Tarpaulin + 1.1x Snow + 1.1x Corrugated Steel Sheeting
- Combination 7 – Self-weight + Tarpaulin + 1.1x Wind + 1.1x Snow + 1.1x Corrugated Steel Sheeting

3.3.7 Structures Analysed

Several variations of the frame are analysed using the above load combinations. As mentioned before, material thickness, pitch, section type and material type are all varied to analyse the difference in stresses in the structure. Table 10 shows the different variations which are analysed. The list below describes the variations shown in the table.

- Structure – The original structure is shown below. Variations to this structure which are analysed include the side ropes and bottom rope being replaced by steel members, the addition of an extra vertical support to the ridge and the storm mode (Figure 28). The storm mode involves lowering the elevation of the shelter by removing one pole from each of the vertical members and using these as extra supports for the ridge.

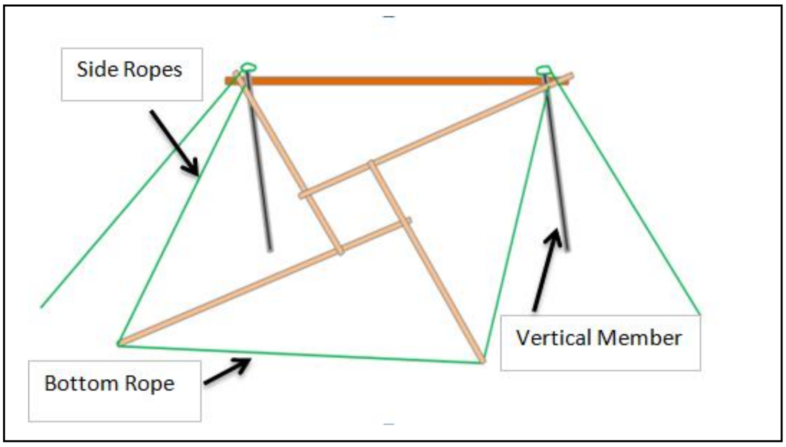


Figure 27; Original Structure

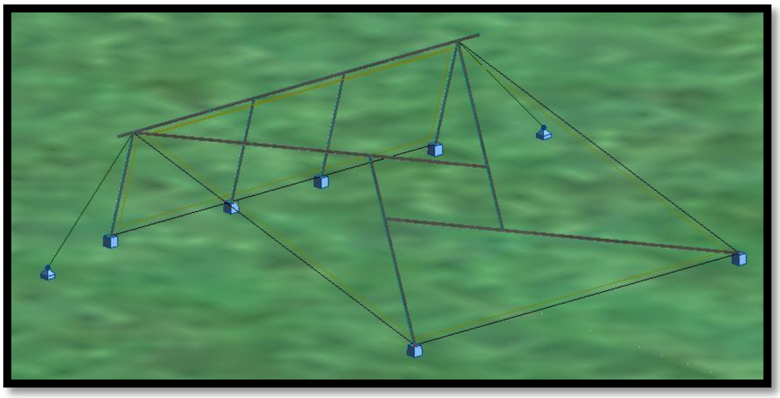


Figure 28; Storm Mode

- Pitch – The angle made between the main face of the structure and the ground. Due to the length of the vertical members used to keep the frame upright, the maximum pitch the structure can reach is 33.75^o. However at this pitch the upright members would be at 90^o to the ground which is not suitable as forces from the frame could cause the upright members to lean forward. Therefore the maximum pitch at which the frame can suitably be constructed is 32^o.
- Material – The frame is analysed using the material properties obtained from the lab testing and also using the properties gathered for bamboo. The material tested in the lab is referred to as ReciproBoo Steel.
- Section – The frame is analysed using tubular and square sections. In order to get a proper insight into which section is better it is required to compare square and tube sections of equivalent areas.
- Thickness (T)– Thickness of the material being analysed.
- Diameter (D)– External diameter of the tube sections. Not relevant for square members.
- Height (H) – External depth of the square sections. Not relevant for tube members.
- Area (A)- Cross-sectional area of the member.
- Yield Strength – If the stress in the members reaches this level failure will occur.

	Structure	Pitch	Material	Section	T (mm)	D (mm)	H (mm)	A (mm^2)	Yield Stress (N/mm^2)
Case 1	Original	30^o	ReciproBoo Steel	Tube	1	22	-	65.97	406
Case 2	Original	30^o	ReciproBoo Steel	Tube	1.5	33	-	97	406
Case 3	Original	30^o	ReciproBoo Steel	Square	1	-	22	84	406
Case 4	Original	30^o	ReciproBoo Steel	Square	1.5	-	22	123	406
Case 5	Side Ropes & Bottom Rope Replaced with Steel Members	30^o	ReciproBoo Steel	Tube	1	22	-	65.97	406
Case 6	Side Ropes Replaced with Steel Members	30^o	ReciproBoo Steel	Tube	1	22	-	65.97	406
Case 7	Extra Vertical Member Supporting Ridge	30^o	ReciproBoo Steel	Tube	1	22	-	65.97	406
Case 8	Original	30^o	Bamboo	Tube	5	50	-	706.5	39.9
Case 9	Original	30^o	Bamboo	Tube	7.5	50	-	1001	39.9
Case 10	Storm Mode	16^o	ReciproBoo Steel	Tube	1	22	-	65.97	406
Case 11	Original	30^o	ReciproBoo Steel	Tube	1	27.73	-	84	406
Case 12	Original	30^o	ReciproBoo Steel	Square	1	-	17.49	65.79	406
Case 13	Original	25^o	ReciproBoo Steel	Tube	1	22	-	65.97	406
Case 14	Original	32^o	ReciproBoo Steel	Tube	1	22	-	65.97	406

Table 10; Structures Analysed

When the above information is input into Autodesk Robot the analysis is ran to determine the stresses, deformations and defections in the frame. The results are given in tabular format and can also be seen mapped on the model of the structure as shown below. Maximum and minimum values are highlighted in red and green.

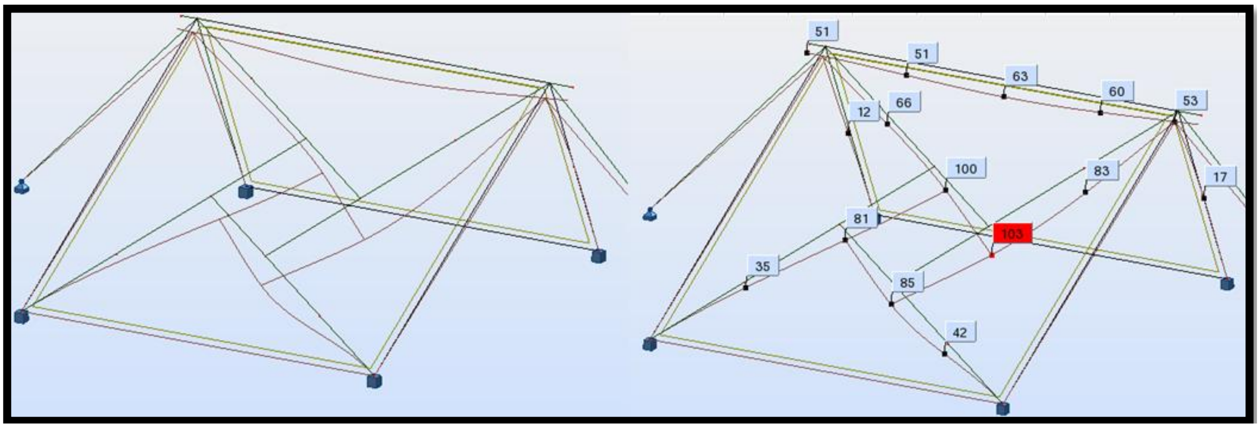


Figure 29; Deformation in Structure

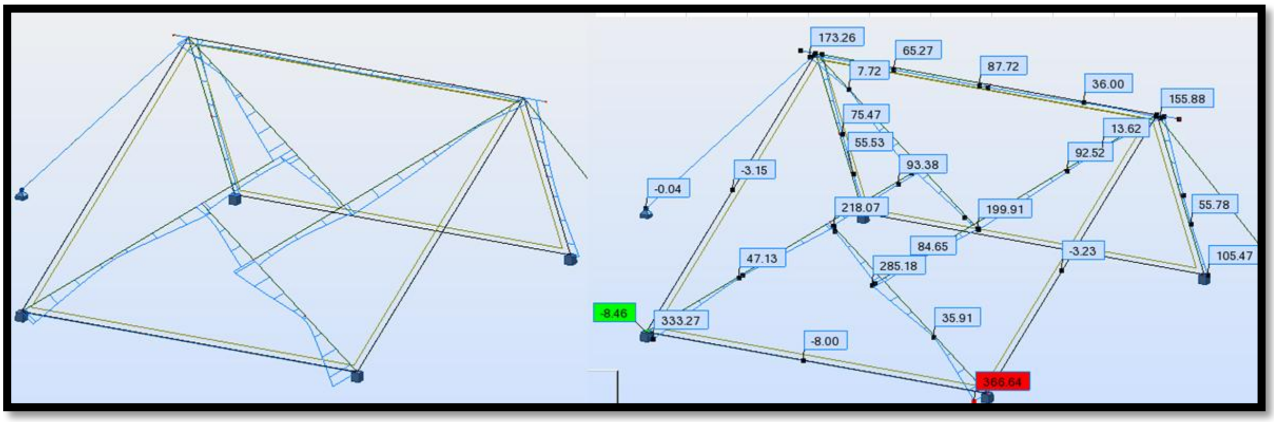


Figure 30; Stresses in Structure

The output from the analysis is examined to determine whether the loads applied cause failure in the frame. Failure is determined by the stresses in the structure – if the stress reaches the yield strength of the material at any point in the structure it means failure has occurred. The results for the different structure combinations are compared to find the areas of the frame most susceptible to failure and the advantages/disadvantages of using different materials and sections.

4 Results

This section will present a summary of the computational results output from Autodesk Robot for the structures analysed under different load combinations. Only maximum values of stress, deformation and deflection are shown. Results highlighted in the tables in green mean that the stress is within the yield stress for the material and therefore the loading does not cause failure of the structure. Results highlighted in red mean the stress has surpassed the yield stress for the material and theoretical failure of the frame has occurred. A full list of stress values for the entire structure can be found in Appendix B. The location of the maximum stresses and deformations are also highlighted in this section.

4.1 Theoretical Stress

Hand calculations were carried out in order to confirm that the frame had been modelled correctly and to ensure the stress output was in the correct range. Table 11 below shows the results of the hand calculations carried out to determine the stress in the outermost fibres of the ridge pole. It is not expected that this result will be identical to the output from Autodesk Robot but it should be close.

Area (A)	0.00006597	m^2
Density (ρ)	7750	kg/m^3
Mass/m length (m)	0.511	kg
Unit Weight (w)	0.005	N/mm
Length (L)	3065	mm
Bending Moment (M)	5889.63	Nmm
Moment of Inertia (Iy)	3548	mm^4
Distance from Centroid (y)	11	mm
Stress (σ)	18.26	MPa

Table 11; Theoretical Stress Calculation

As can be seen from above, the theoretical stress in the ridge pole is calculated to be 18.26 MPa. Analysis of the frame under its self-weight in Autodesk Robot gives a stress output for the ridge ranging from approximately 5MPa to 11MPa. Taking into account that the effects of joints and connections in the ridge are not considered in the theoretical calculation these results are accurate enough to suggest that the structure has been modelled correctly. This allows further, more detailed analysis to be carried out.

4.2 Location of Maximum Stress and Deformation

The diagrams below show the locations of the maximum stress and maximum deformations in the frame when subject to various different loadings.

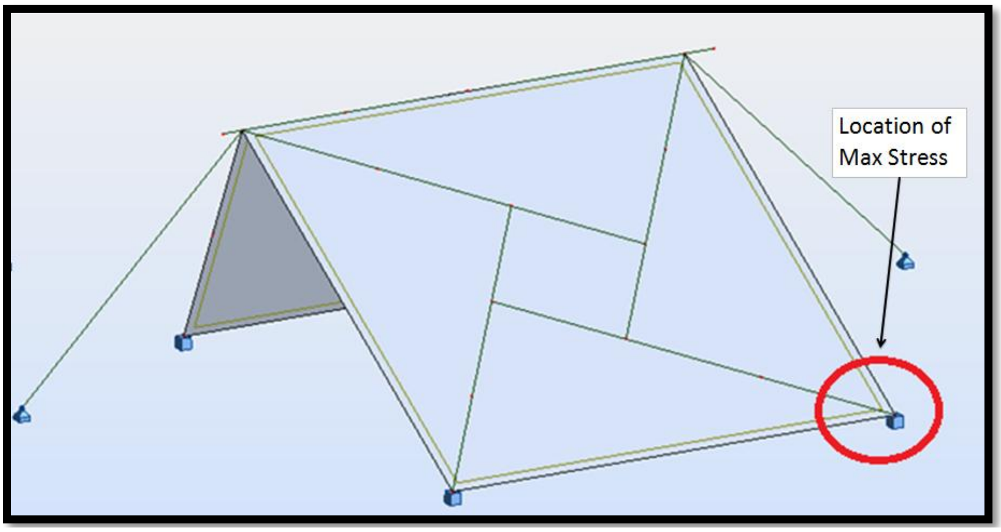


Figure 31; Maximum Stress Location

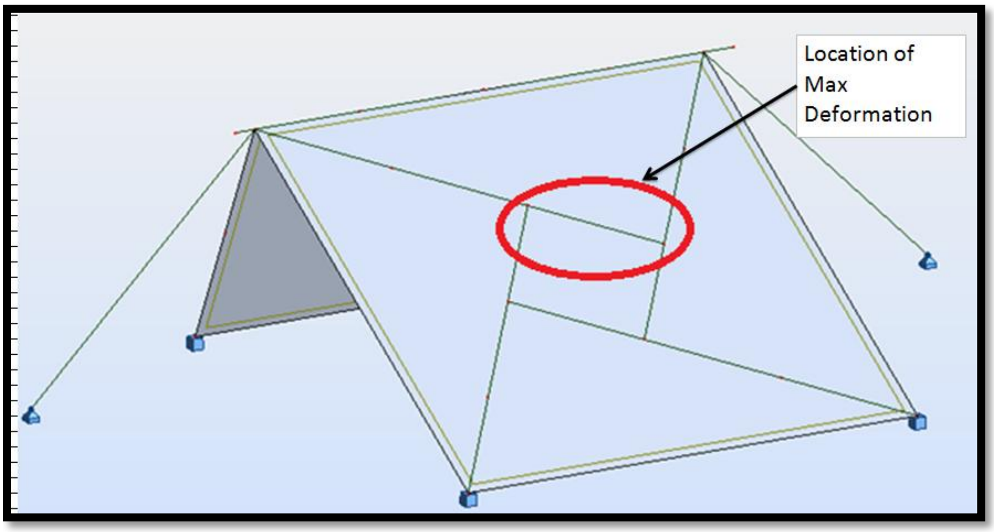


Figure 32 - Maximum Deformation Location

4.3 Computational Results Summary

4.3.1 Case 1

Structure: Original Pitch: 30° Material: ReciproBoo Steel Section: Tube

Diameter: 22mm Thickness: 1mm Area: 66mm^2 Yield Strength: 406 MPa

	Bars			Cables
	Max Stress (Mpa)	Max Displacement (mm)	Max Deflection (mm)	Max Stress (Mpa)
LC1	60.27	19	1	-1.14
LC2	422.94	134	9	-9.31
LC3	366.64	120	9	-8.46
LC4	326.21	103	7	-7.49
LC5	701.77	228	16	-13.98
LC6	667.66	212	14	-13.5
LC7	940.74	305	22	-17.66

4.3.2 Case 2

Structure: Original Pitch: 30° Material: ReciproBoo Steel Section: Tube

Diameter: 22mm Thickness: 1.5mm Area: 97mm^2 Yield Strength: 406 MPa

	Bars			Cables
	Max Stress (Mpa)	Max Displacement (mm)	Max Deflection (mm)	Max Stress (Mpa)
LC1	54.71	17	1	-1.14
LC2	318.94	101	7	-9.31
LC3	277.6	91	7	-8.46
LC4	248.77	78	6	-7.49
LC5	520.39	169	12	-13.98
LC6	496	157	11	-13.5
LC7	692.96	224	16	-17.66

4.3.3 Case 3

Structure: Original Pitch: 30° Material: ReciproBoo Steel Section: Square

Height: 22mm Thickness: 1mm Area: 84mm^2 Yield Strength: 406 MPa

	Bars			Cables
	Max Stress (Mpa)	Max Displacement (mm)	Max Deflection (mm)	Max Stress (Mpa)
LC1	59.14	13	1	-1.14
LC2	369.47	83	6	-9.31
LC3	310.58	75	5	-8.46
LC4	287.68	64	5	-7.49
LC5	591.55	140	10	-13.98
LC6	574.81	131	9	-13.5
LC7	789.88	187	13	-17.66

4.3.4 Case 4

Structure: Original Pitch: 30° Material: ReciproBoo Steel Section: Square

Height: 22mm Thickness: 1.5mm Area: 123mm^2 Yield Strength: 406 MPa

	Bars			Cables
	Max Stress (Mpa)	Max Displacement (mm)	Max Deflection (mm)	Max Stress (Mpa)
LC1	54.3	12	1	-1.14
LC2	280.8	63	5	-9.31
LC3	238.2	57	4	-8.46
LC4	221.29	49	4	-7.49
LC5	442.5	104	7	-13.98
LC6	429.87	97	7	-13.5
LC7	586.3	138	10	-17.66

4.3.5 Case 5

Structure: Side & Bottom ropes replaced with steel members

Pitch: 30° Material: ReciproBoo Steel Section: Tube

Diameter: 22mm Thickness: 1mm Area: $66mm^2$ Yield Strength: 406 MPa

	Bars			Cables
	Max Stress (Mpa)	Max Displacement (mm)	Max Deflection (mm)	Max Stress (Mpa)
LC1	41.52	13	1	-0.14
LC2	305.11	93	8	-0.15
LC3	306.02	94	8	-0.15
LC4	231.44	71	6	-0.15
LC5	569.55	174	15	-0.16
LC6	495.03	151	13	-0.16
LC7	759.46	232	20	-0.17

4.3.6 Case 6

Structure: Side ropes replaced with steel members

Pitch: 30° Material: ReciproBoo Steel Section: Tube

Diameter: 22mm Thickness: 1mm Area: $66mm^2$ Yield Strength: 406 MPa

	Bars			Cables
	Max Stress (Mpa)	Max Displacement (mm)	Max Deflection (mm)	Max Stress (Mpa)
LC1	41.52	13	1	-0.87
LC2	305.13	93	8	-6.23
LC3	306.04	94	8	-5.69
LC4	231.46	71	6	-5.06
LC5	569.59	174	15	-9.16
LC6	495.07	151	13	-8.86
LC7	759.52	232	20	-11.40

4.3.7 Case 7

Structure: Extra vertical member supporting ridge

Pitch: 30° Material: ReciproBoo Steel Section: Tube

Diameter: 22mm Thickness: 1mm Area: 66mm^2 Yield Strength: 406 MPa

	Bars			Cables
	Max Stress (Mpa)	Max Displacement (mm)	Max Deflection (mm)	Max Stress (Mpa)
LC1	58.27	18	1	-1.14
LC2	409.58	126	9	-9.31
LC3	356.75	113	8	-8.46
LC4	315.9	97	7	-7.49
LC5	681.81	215	16	-13.98
LC6	646.59	200	14	-13.50
LC7	913.39	287	21	-17.66

4.3.8 Case 8

Structure: Original Pitch: 30° Material: Bamboo Section: Tube

Diameter: 50mm Thickness: 5mm Area: 706.5mm^2 Yield Strength: 39.9 MPa

	Bars			Cables
	Max Stress (Mpa)	Max Displacement (mm)	Max Deflection (mm)	Max Stress (Mpa)
LC1	3.04	4	0	-1.14
LC2	21.58	27	2	-9.31
LC3	18.41	24	2	-8.46
LC4	16.74	21	2	-7.49
LC5	35.07	46	3	-13.98
LC6	33.68	42	3	-13.5
LC7	46.8	61	4	-17.66

4.3.9 Case 9

Structure: Original Pitch: 30° Material: Bamboo Section: Tube

Diameter: 50mm Thickness: 7.5mm Area: 1001mm^2 Yield Strength: 39.9 MPa

	Bars			Cables
	Max Stress (Mpa)	Max Displacement (mm)	Max Deflection (mm)	Max Stress (Mpa)
LC1	2.84	4	0	-1.14
LC2	17.39	22	2	-9.31
LC3	14.89	20	1	-8.46
LC4	13.6	17	1	-7.49
LC5	27.94	36	2	-13.98
LC6	26.86	34	2	-13.5
LC7	37.1	48	3	-17.66

4.3.10 Case 10

Structure: Storm Mode Pitch: 30° Material: ReciproBoo Steel Section: Tube

Diameter: 22mm Thickness: 1mm Area: 66mm^2 Yield Strength: 406 MPa

	Bars			Cables
	Max Stress (Mpa)	Max Displacement (mm)	Max Deflection (mm)	Max Stress (Mpa)
LC1	47.09	15	1	-0.95
LC2	351.41	105	8	-6.95
LC3	317.21	95	8	-6.44
LC4	264.03	79	6	-5.62
LC5	622.39	185	15	-10.54
LC6	568.44	170	13	-9.83
LC7	839.3	250	20	-13

4.3.11 Case 11

Structure: Original   Pitch: 30°   Material: ReciproBoo Steel   Section: Tube

Diameter: 27.3mm   Thickness: 1mm   Area: 84mm^2 Yield Strength: 406 MPa

	Bars			Cables
	Max Stress (Mpa)	Max Displacement (mm)	Max Deflection (mm)	Max Stress (Mpa)
LC1	44.2	11	1	-1.14
LC2	276.77	69	5	-9.31
LC3	239.52	62	4	-8.46
LC4	215.39	53	4	-7.49
LC5	451.7	116	8	-13.98
LC6	431.25	108	7	-13.5
LC7	602	154	11	-17.66

4.3.12 Case 12

Structure: Original   Pitch: 30°   Material: ReciproBoo Steel   Section: Square

Height: 17.49mm   Thickness: 1mm   Area: 66mm^2 Yield Strength: 406 MPa

	Bars			Cables
	Max Stress (Mpa)	Max Displacement (mm)	Max Deflection (mm)	Max Stress (Mpa)
LC1	80.79	23	1	-1.14
LC2	564.2	162	11	-9.31
LC3	469	146	11	-8.46
LC4	435.61	124	9	-7.49
LC5	911.57	276	20	-13.98
LC6	888.67	257	17	-13.5
LC7	1226.19	370	26	-17.66

4.3.13 Case 13

Structure: Original Pitch: 25° Material: ReciproBoo Steel Section: Tube

Diameter: 22mm Thickness: 1mm Area: 66mm^2 Yield Strength: 406 MPa

	Bars			Cables
	Max Stress (Mpa)	Max Displacement (mm)	Max Deflection (mm)	Max Stress (Mpa)
LC1	57.63	19	1	-0.95
LC2	408.13	132	9	-6.96
LC3	353.19	115	9	-6.43
LC4	307.67	100	7	-5.62
LC5	701.44	229	16	-10.38
LC6	659.45	214	15	-9.89
LC7	951.9	310	22	-12.88

4.3.14 Case 14

Structure: Original Pitch: 32° Material: ReciproBoo Steel Section: Tube

Diameter: 22mm Thickness: 1mm Area: 66mm^2 Yield Strength: 406 MPa

	Bars			Cables
	Max Stress (Mpa)	Max Displacement (mm)	Max Deflection (mm)	Max Stress (Mpa)
LC1	57.77	18	1	-0.87
LC2	418.88	131	9	-6.23
LC3	369.29	120	9	-5.74
LC4	320.39	100	7	-5.03
LC5	701.6	226	16	-9.17
LC6	660.51	208	14	-8.84
LC7	937.04	301	21	-11.38

5 Analysis of Results

In this section the results output from Autodesk Robot are analysed. The structures performance is compared under different conditions such as material type, material thickness, section type and the effects of adding additional members to the frame.

5.1 Material Thickness

Table 12 shows the comparisons in stress in similar sections with different thicknesses' using the same material. The stresses in tubular sections are compared under different load combinations and the percentage reduction in stress due to the increased thickness is also shown. The same comparisons are made for the square sections which the frame was modelled with in Autodesk Robot. Due to the fact that the same increase in thickness in the square members as the tube members will result in a larger cross-sectional area increase in the square members, it is expected that the increase in strength will be greater in the case of square sections.

Thickness Comparisons							
	Tubes-30^{o}-1mm	Tubes-30^{o}-1.5mm			Square-30^{o}-1mm	Square-30^{o}-1.5mm	
	Max Stress (Mpa)	Max Stress (Mpa)	% Reduction		Max Stress (Mpa)	Max Stress (Mpa)	% Reduction
LC1	60.27	54.71	9.23		59.14	54.3	9.91
LC2	422.94	318.94	24.59		369.47	280.8	33.61
LC3	366.64	277.6	24.29		310.58	238.2	35.03
LC4	326.21	248.77	23.74		287.68	221.29	32.16
LC5	701.77	520.39	25.85		591.55	442.5	36.95
LC6	667.66	496	25.71		574.81	429.87	35.62
LC7	940.74	692.96	26.34		789.88	586.3	37.68

Table 12; Thickness Comparisons

As can be seen clearly from the above table a small increase in material thickness results in a significant increase in the strength of the members. In the case of the tube sections, an increase of 0.5 mm in thickness leads to an average reduction in stress of 22.8% depending on the loading scenario. For square section members, a thickness increase of 0.5 mm also leads to an average reduction in the stresses in the members of 31.6%.

These figures are very significant as they show that the strength of individual members and therefore the entire structure can be vastly increased by increasing the thickness of members minimally. Although the increase in thickness will add to the weight of the frame, the noteworthy increase in strength is very important and is seriously worth considering as an option for increasing the strength of the current frame.

5.2 Section Variations

This analysis compares the performance of different section types for use in this structure. The stresses in square and tubular members are compared under the same loading firstly using similar dimensions- 22mm diameter x 1mm thick tube sections v 22mm deep x 1mm thick square sections. Due to the fact that the square sections have a larger cross-sectional area than the tube sections, samples of both with equal cross-sectional areas are also compared. This is to identify which types of section is best for resisting the forces produced in the frame under loading. The performance of each section is analysed by investigating how much of the materials stress capacity is utilised for a given section under different load combinations. Obviously the lower the stress utilisation in the section the better the section is at resisting the applied load and the more suitable the section is for use in this frame.

Section Comparisons								
	Tube-30^{o}-1mm		Tube-30^{o}-1.5mm		Square-30^{o}-1mm		Square-30^{o}-1.5mm	
	Max Stress (Mpa)	Stress Utilisation (%)	Max Stress (Mpa)	Stress Utilisation (%)	Max Stress (Mpa)	Stress Utilisation (%)	Max Stress (Mpa)	Stress Utilisation (%)
LC1	60.27	14.77	54.71	13.41	59.14	14.50	54.3	13.31
LC2	422.94	103.66	318.94	78.17	369.47	90.56	280.8	68.82
LC3	366.64	89.86	277.60	68.04	310.58	76.12	238.2	58.38
LC4	326.21	79.95	248.77	60.97	287.68	70.51	221.3	54.24
LC5	701.77	172.00	520.39	127.55	591.55	144.99	442.5	108.46
LC6	667.66	163.64	496.00	121.57	574.81	140.88	429.9	105.36
LC7	940.74	230.57	692.96	169.84	789.88	193.60	586.3	143.70

Table 13; Section Comparisons

As can be seen from Table 13 above the stress utilisation in the square members is significantly less than in the tubular sections. This indicates that the square sections are much more effective at resisting the loads applied to the structure from different load combinations. The extra resistance to the applied loads supplied by the square members is more than likely due to the additional cross-sectional area which accompanies this section type. Although this added cross-sectional area will also result in additional weight, it is worth remembering that the square sections can be transported in the same size packaging as the tubular members and in fact utilise the space in the packaging more efficiently.

The performance of the different section types with equivalent areas is investigated in Table 14 below. A 22mm diameter tube with a material thickness of 1mm has the same cross-sectional area as a 17.5mm deep square section with 1mm thickness. Also a 22mm deep square section with 1mm thick material has the same cross-sectional area as a 27.73mm diameter tube with the same thickness of material.

Section Comparisons-Equivalent Areas								
	Tubes-30^{o}-1mm-66mm^2		Square-30^{o}-1mm-66mm^2		Tubes-30^{o}-1mm-84mm^2		Square-30^{o}-1mm-84mm^2	
	Max Stress (Mpa)	Stress Util. (%)	Max Stress (Mpa)	Stress Util. (%)	Max Stress (Mpa)	Stress Util. (%)	Max Stress (Mpa)	Stress Util. (%)
LC1	60.27	14.77	80.79	19.80	44.2	10.83	59.14	14.50
LC2	422.94	103.66	564.2	138.28	276.77	67.84	369.47	90.56
LC3	366.64	89.86	469	114.95	239.52	58.71	310.58	76.12
LC4	326.21	79.95	435.61	106.77	215.39	52.79	287.68	70.51
LC5	701.77	172.00	911.57	223.42	451.7	110.71	591.55	144.99
LC6	667.66	163.64	888.67	217.81	431.25	105.70	574.81	140.88
LC7	940.74	230.57	1226.19	300.54	602	147.55	789.88	193.60

Table 14; Section Comparisons - Equivalent Areas

As can be seen from the above data, the stress utilisation in the tubular sections tends to be quite lower than the square sections when both are subject to the same loading. This implies that the square members will reach failure at a lower load than the tubular members even though the cross-sectional areas in both are the same. The reason for this is that in square or rectangular sections, stresses tend to accumulate around the bend/corner in the material. This results in the stresses being greater at these points than in the flat parts of the section causing failure at these locations first. In tubular sections however, the stresses are distributed evenly throughout the material enabling it to withstand a greater load without reaching failure.

The above analysis provides evidence to suggest that both square and tubular sections are viable options for use in construction of the ReciproBoo frame. Tubular sections are more effective when dealing with equivalent cross-sectional areas but square sections utilise packing space more efficiently. They are also capable of providing extra resistance due to its greater cross-sectional area.

5.3 Material Types – Steel v Bamboo

The frame was modelled using bamboo properties in an attempt to observe whether or not it is a feasible option for use in the construction of the ReciproBoo frame. Table 15 below shows the percentage of the yield stress which is utilised under different load combinations for both steel and bamboo.

Material Comparisons								
	Tubes-30^o-1mm		Tubes-30^o-1.5mm		Bamboo-30^o-5mm		Bamboo-30^o-7.5mm	
	Max Stress (Mpa)	Stress Util. (%)	Max Stress (Mpa)	Stress Util. (%)	Max Stress (Mpa)	Stress Util. (%)	Max Stress (Mpa)	Stress Util. (%)
LC1	60.27	14.77	54.71	13.41	3.04	7.62	2.84	7.12
LC2	422.94	103.66	318.94	78.17	21.58	54.09	17.39	43.58
LC3	366.64	89.86	277.60	68.04	18.41	46.14	14.89	37.32
LC4	326.21	79.95	248.77	60.97	16.74	41.95	13.60	34.09
LC5	701.77	172.00	520.39	127.55	35.07	87.89	27.94	70.03
LC6	667.66	163.64	496.00	121.57	33.68	84.41	26.86	67.32
LC7	940.74	230.57	692.96	169.84	46.80	117.29	37.10	92.98

Table 15; Material Comparisons

The above evidence suggests that bamboo is most definitely a suitable material for use in this structure. In fact this data implies that it is a better more appropriate alternative to using steel members in the construction of the frame. However, while the strength of this material is hugely impressive it is certainly worthwhile keeping in mind that the material properties input into Autodesk Robot are just average values for a range of possible values for bamboo. Due to the huge range of different species and strengths of bamboo it would be very possible to encounter bamboo with a much lower strength than that which is modelled in Autodesk Robot in this case. It is also relevant to note that the properties of bamboo are likely to vary with time as the material dries out. Also bamboo can be susceptible to insect attack if not treated correctly which would lead to a large reduction in strength.

For a more permanent solution steel is the most suitable material as there is greater certainty regarding the strength of the material compared to bamboo. However in cases where the frame is required only on a temporary basis then bamboo is without doubt a suitable option.

5.4 Affects of Additional Members

This section analyses how the addition of extra members to the original frame affects the overall strength of the structure. The frame was modelled with the side ropes and bottom ropes replaced by steel members and also with only the side ropes replaced to investigate whether a significant increase in strength could be obtained from such adjustments. The addition of an extra vertical member to support the ridge pole is also evaluated in an attempt to find a stronger combination for the frame. Table 16 below shows the maximum stress in each of the altered combinations compared to the original configuration under the same loading. The improvement in strength of the frame due to the extra members is shown as the percentage reduction in the maximum stress in the structure compared to the stress in the original design.

Additional Members Comparisons							
	Tube-30°-1mm	Side & Bottom Ropes Replaced-Tube-30°-1mm		Side Ropes Replaced-Tube-30°-1mm		Extra Vert. Member-Tube-30°-1mm	
	Max Stress (Mpa)	Max Stress (Mpa)	% Improvement on Original	Max Stress (Mpa)	% Improvement on Original	Max Stress (Mpa)	% Improvement on Original
LC1	60.27	41.52	31.11	41.52	31.11	58.27	3.32
LC2	422.94	305.11	27.86	305.13	27.86	409.58	3.16
LC3	366.64	306.02	16.53	306.04	16.53	356.75	2.70
LC4	326.21	231.44	29.05	231.46	29.05	315.9	3.16
LC5	701.77	569.55	18.84	569.59	18.84	681.81	2.84
LC6	667.66	495.03	25.86	495.07	25.85	646.59	3.16
LC7	940.74	759.46	19.27	759.52	19.26	913.39	2.91

Table 16; Additional Members Comparisons

As can be seen from the above comparisons there are advantages to be gained in terms of strength from all of the variations tested in Autodesk Robot. However the results from the model in which the side ropes and bottom ropes are replaced with steel members show almost identical results to the model in which only the side ropes are replaced. This indicates that the addition of steel members instead of the bottom ropes makes little or no difference to the overall strength of the structure. But replacing the side ropes with steel members provides a significant increase in strength of the frame. The maximum stress under these circumstances is on average 24% less than in the original configuration depending on the loads present. This signifies that adding in steel members instead of the side ropes is an option which needs to be seriously considered. The data above proves that considerable extra strength and rigidity will be achieved by doing so and will enable the frame to withstand extra loading without failure.

In the case of adding in an extra vertical steel member to support the ridge there is also a decrease in the maximum stress in the structure. However, the average decrease in stress is only 3% on average and therefore does not significantly change the strength of the structure. As a result this option is not worthwhile up taking as only minimal advantages can be gained.

5.5 Strength at Different Pitches

The structure was tested at different pitches under the various load combinations to determine whether or not the pitch of the frame relates to its strength, and if so what is the optimum pitch to maximise its strength. The different pitches at which the frame can be constructed are limited due to the length of the vertical members keeping it upright. As a result the frame was only tested at 25^o, 30^o and 32^o. Table 17 below shows the results for the maximum stress in the frame at these pitches and the percentage of the yield stress which is utilised under different load combinations is also shown for different pitches.

Pitch Comparisons						
	Tube-30^o-1mm		Tube-25^o-1mm		Tube-32^o-1mm	
	Max Stress (Mpa)	Stress Util. (%)	Max Stress (Mpa)	Stress Util. (%)	Max Stress (Mpa)	Stress Util. (%)
LC1	60.27	14.84	57.63	14.19	57.77	14.23
LC2	422.94	104.17	408.13	100.52	418.88	103.17
LC3	366.64	90.31	353.19	86.99	369.29	90.96
LC4	326.21	80.35	307.67	75.78	320.39	78.91
LC5	701.77	172.85	701.44	172.77	701.6	172.81
LC6	667.66	164.45	659.45	162.43	660.51	162.69
LC7	940.74	231.71	951.9	234.46	937.04	230.80

Table 17; Pitch Comparisons

As can be seen from the above data the pitch at which the frame is constructed does not have a major influence in terms of the structures strength. Although the stresses vary slightly depending on the pitch there is not enough evidence to suggest that the strength varies significantly as the pitch increases or decreases. Therefore it can be concluded that the pitch is not overly important when considered in terms of the frames strength.

5.6 Ropes/Cables

The analysis carried out in Autodesk Robot also includes values for stresses in the guy ropes and side ropes which make up part of the frame. Under all the different load combinations the ropes don't come anywhere near failure. This implies that the material used in the ropes is very suitable. Table 18 below shows the amount of the ropes tensile capacity used when the frame is subject to various load combinations.

	Side Ropes		Guy Ropes	
	Max Stress (Mpa)	Utilisation (%)	Max Stress (Mpa)	Utilisation (%)
LC1	-1.14	1.57	-0.1	0.10
LC2	-9.31	12.84	-0.06	0.06
LC3	-8.46	11.67	-0.06	0.06
LC4	-7.49	10.33	-0.07	0.07
LC5	-13.98	19.28	-0.05	0.05
LC6	-13.5	18.62	-0.06	0.06
LC7	-17.66	24.36	-0.05	0.05

Table 18; Rope Stresses

5.7 Sources of Error

As with all experimental procedures there is a possibility that errors may have occurred during implementation which may slightly affect the results output. In addition, the assumptions used when modelling the frame may have led to some errors in the computational results.

- Material testing – It would have been desirable to have more samples upon which to carry out laboratory testing. As tests were carried out on only two bar samples and one of each guy rope and side rope samples. As a result the findings are not as accurate as they would be if a large number of tests were carried out.
- Bamboo properties – Due to the large range of bamboo species an average value for a range of possible values was taken when modelling bamboo. More accurate results would arise from modelling specific species of bamboo.
- Assumptions made – Inaccuracies may occur in the modelling results due to the assumptions made when constructing the frame in Autodesk Robot. Particularly in the assumption that the connections between members are fully rigid when in reality

a small amount of rotation is present. Also the assumption that the cross-lashed joints are fully rigid when in reality it depends on the standard to which it is tied.

6 Conclusions

From the literature review it can be concluded that there is in fact a great need for the ReciproBoo shelter kit and it is felt that it would be of significant interest to humanitarian aid agencies to invest in the further development of this product. As highlighted in the literature review, a strong, light-weight, workable and cheap shelter could prove much more suitable in some of the world's humanitarian emergencies than some of the larger humanitarian relief tents which are distributed in the modern day. This is largely due to the fact that studies have found that many people move out of these semi-permanent homes and into self built homes which have been constructed using local materials after a short period of time. A shelter such as the ReciproBoo which can be distributed at a low cost in huge quantities to situations of great urgency such as natural disasters can effectively 'buy time' for aid agencies. This allows them to carry out assessments on the appropriate type of permanent shelters to be constructed. This will ultimately help aid agencies to save on resources which can then be put into other areas of relief such as healthcare, sanitation and food.

It was concluded during the project that there were certain limitations to our own project, including time and finances, and going forward there are most definitely areas where future studies could be worthwhile. As we were forced to make assumptions when analysing the bamboo, due to its variability, it is felt that there is room for further study and analysis of bamboo as a structural component of the ReciproBoo frame. The cross lashed joints and the spring loaded joints are another part of the ReciproBoo product which could allow for further research and development. Another limitation to the project was the fact that we could not destruct more of the steel rods or indeed a full frame during testing. As a result it is felt that there is further room for research in the testing of prototypes of the ReciproBoo frame by varying section types and thicknesses and indeed material types. This type of research will require a reasonable amount of finances.

After assembling the ReciproBoo frame it was concluded that there is excessive slack in the spring loaded joints between each member however this fault was hugely outweighed by the advantages of the frame. It can be concluded that the frame is extremely easy to assemble, is very light for transportation, and could be easily repaired in the event of damage being caused. It can also be concluded that even with the slack in the spring loaded joints, the frame will be able to withstand reasonable forces from insulating materials such as corrugated steel or reeds and other vegetation.

The analysis of the frame using Autodesk Robot proved to be very beneficial and a number of conclusions have been drawn from this analysis. Firstly it can be concluded that increasing the thickness of the structural materials used provides a huge difference to the strength of the structure. It was found that when the thickness of the tubular sections is increased by 0.5mm the average reduction in the maximum stress is 22.8%. Similarly, a 0.5mm increase to the thickness of the square section steel lead to an average reduction in the stresses in each member of 31.6%.

Using the Autodesk Robot analysis it was also found that when the frame is made up of 22mm x 22mm x 1mm square sections the utilisation ratios of the steel were lower than when compared to 22mm diameter tubular sections. In other words the squares sections had reached less of a percentage of their capacity. However when the square sections were reduced to 17.5mm x 17.5mm x 1mm, the same cross sectional area as the 22mm diameter tubular sections, the utilisation of the square sections proved to be higher. It can be concluded that when square and tubular sections of the same cross sectional area are used, the tubular sections are in fact stronger.

It can be concluded from the computational analysis that the pitch of the structure does not have a very big influence on the load bearing capabilities of the frame. When the structure was analysed under varying pitches and loads it was found that there were small but largely insignificant differences in the maximum stresses in the members.

The use of bamboo to replace the steel components of the frame showed some interesting results. It can most definitely be concluded that bamboo is a very good alternative to the steel members in the ReciproBoo. When analysed under varying load combinations it was found that the bamboo with a thickness of 5mm and a diameter of 50mm had almost half the utilisation ratio of a 22mm diameter, 1mm thick tubular section showing that it is extremely rigid and has huge load bearing capabilities.

Interesting conclusions can also be drawn from the replacement of the side ropes. When the side ropes and bottom rope of the frame were replaced with 22m diameter, 1mm thick tubular steel there was an average reduction in the maximum stresses in the frame of 24%. Interestingly, when the bottom rope was left in its original form there was very little difference in the average reduction in maximum stresses. It can therefore be concluded that replacing the side ropes with a material such as steel or bamboo is very beneficial to the structure while replacing the bottom rope is of little or no addition.

To summarise, the purpose of this project was to analyse a reciprocal roof framed shelter for use in humanitarian emergencies. It is felt that a thorough analysis of the structure has been carried out from a theoretical, practical and structural point of view. A number of aims were highlighted in the introduction of this report and it is felt that these aims and objectives were achieved. To conclude, the ReciproBoo shelter is most definitely suitable for use in humanitarian emergencies worldwide and is a very important development in the area of humanitarian relief. The load bearing capabilities of the frame due its reciprocal shape and a host of benefits have resulted in a shelter which is very well adapted to suit humanitarian emergencies. It is therefore of great importance that aid agencies consider the advantages of this shelter kit or at least take the concept on board.

7 Recommendations

It is highly recommended that an effort is made to source a supplier for the steel members who can manufacture the spring loaded joints with more precision in order to maximise the potential of the frame. Although the performance of the frame is very impressive using the members currently supplied, significant advantages in terms of the frames strength and rigidity can be gained from the use of members with little, or preferably no slack in the joints.

As a result of the computational results obtained from Autodesk Robot it is recommended that tubular members with an increased thickness of 0.5mm are used or at least tried out in the form of a prototype. Although this will increase the overall weight of the structure the advantages in terms of strength largely overshadow this.

There are vast advantages associated with the replacement of the side ropes with steel members and so it is recommended that this be considered in future manufacture of the frame. Similar to the effects of increasing the thickness of the material this will also increase the weight of the frame. However it is difficult to look past the effects in terms of strength and stability that accompanies this modification.

Even though the performance of the cross-lashed joints proved very suitable during our construction of the frame it is recommended that an alternative solution is considered. The possible variations in the strength of the joint depending on the person tying them makes it difficult to have full confidence in the joints. If after some research and development a suitably strong, practical and cheap method of joining the members is found, it should be implemented in the design of the ReciproBoo frame. However if such a solution cannot be formulated then the cross-lashed joints will be sufficiently strong as long as they are constructed to a good standard.

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United Nations Global Appeal 2012-2013

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United Nations High Commissioner for Refugees (UNHCR) Global Report 2010

www.reciproboo.org

http://www.rnw.nl/english/article/african-union-agrees-internal-refugees-treaty

http://www.telegraph.co.uk/news/worldnews/centralamericaandthecaribbean/haiti

BS6399 Part 2 - Table 2 Dynamic Wind Pressures

9 Appendix A – Computational Results: Case 1

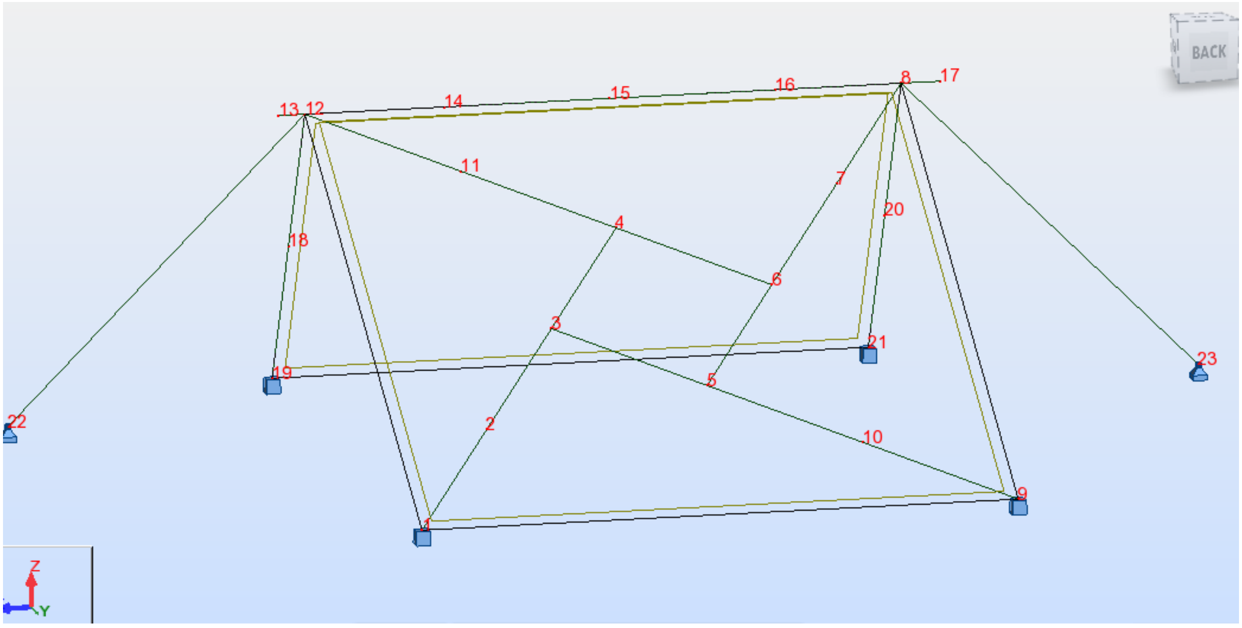

Figure 33; Node Numbering

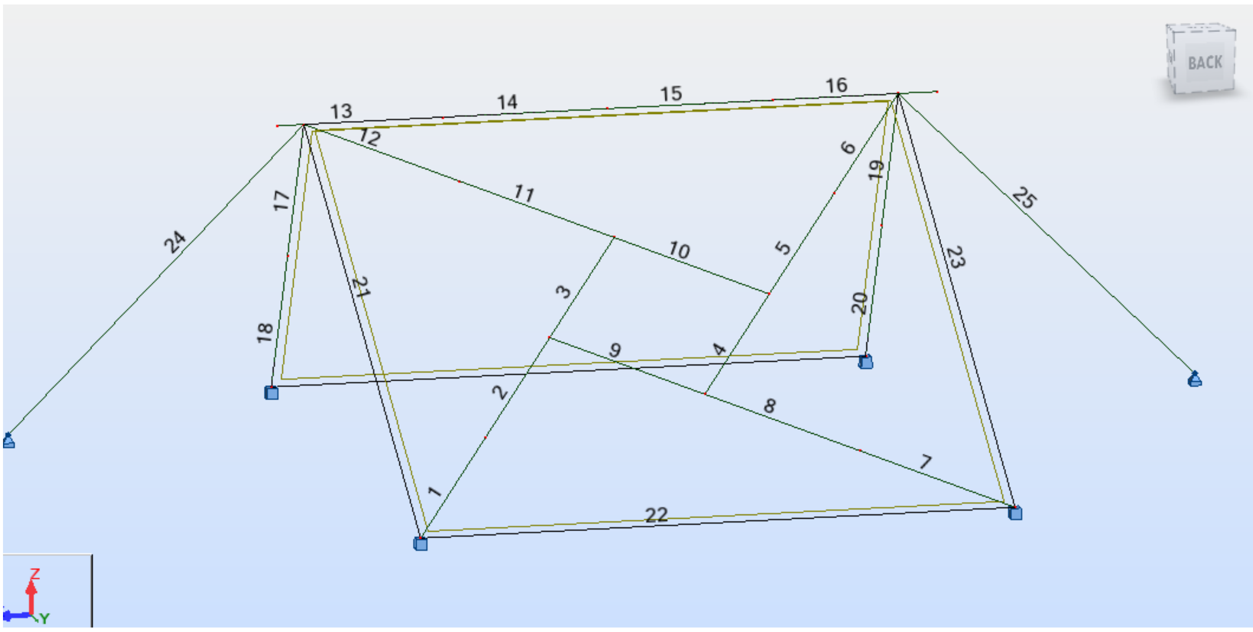

Figure 34; Bar Numbering

LC1: SW+Tarp		
Stresses		
Bar/Node/Case	S max (MPa)	S min (MPa)
1/1/6	47.82	-46.24
1/2/6	9.34	-7.83
2/2/6	9.34	-7.83
2/3/6	40.44	-39.02
3/3/6	27.09	-26.13
3/4/6	26.22	-25.34
4/5/6	25.42	-24.59
4/6/6	29.95	-29.2
5/6/6	37.42	-36.36
5/7/6	19.2	-18.22
6/7/6	19.2	-18.22
6/8/6	15.5	-14.58
7/10/6	8.35	-6.89
7/9/6	60.27	-58.76
8/5/6	53.87	-52.46
8/10/6	8.35	-6.89
9/3/6	15.45	-14.57
9/5/6	31.36	-30.43
10/4/6	29.99	-29.51
10/6/6	9.73	-9.2
11/11/6	14.46	-13.54
11/4/6	52.11	-51.13
12/12/6	28.67	-27.79
12/11/6	14.46	-13.54
13/13/6	0	0
13/14/6	12.62	-12.99
14/14/6	12.62	-12.99
14/15/6	21.78	-22.15
15/15/6	21.78	-22.15
15/16/6	8.53	-8.9
16/16/6	8.53	-8.9
16/17/6	0	0
17/18/6	12.81	-11.77
17/12/6	26.02	-25.1
18/19/6	18.99	-17.83
18/18/6	12.81	-11.77
19/20/6	12.57	-11.44
19/8/6	34.81	-33.8
20/21/6	26.82	-25.58
20/20/6	12.57	-11.44
21/12/6	-0.41	-0.41
21/1/6	-0.36	-0.36
22/1/6	-1.14	-1.14
22/9/6	-1.13	-1.13
23/8/6	-0.4	-0.4
23/9/6	-0.35	-0.35
24/12/6	-0.1	-0.1
24/22/6	-0.09	-0.09
25/8/6	-0.06	-0.06
25/23/6	-0.05	-0.05

Displacements-Nodes			
Node/Case	UX (mm)	UY (mm)	UZ (mm)
1/6	0	0	0
2/6	1	-4	-5
3/6	0	-7	-13
4/6	-6	-5	-17
5/6	4	-2	-15
6/6	-2	0	-19
7/6	-4	5	-15
8/6	-2	9	-4
9/6	0	0	0
10/6	3	0	-7
11/6	-5	-1	-12
12/6	-2	8	-4
13/6	-2	9	-3
14/6	-2	6	-10
15/6	-2	7	-14
16/6	-2	8	-10
17/6	-2	9	-3
18/6	1	2	-1
19/6	0	0	0
20/6	-2	2	-1
21/6	0	0	0
22/6	0	0	0
23/6	0	0	0

Deflections- Bars			
Bar/Case	UX (mm)	UY (mm)	UZ (mm)
1/6	0	1	0
2/6	0	-1	-1
3/6	0	-1	0
4/6	0	-1	0
5/6	0	-1	1
6/6	0	0	0
7/6	0	1	-1
8/6	0	-1	1
9/6	0	-1	0
10/6	0	-1	0
11/6	0	-1	-1
12/6	0	0	0
13/6	0	0	-1
14/6	0	-1	0
15/6	0	-1	0
16/6	0	0	0
17/6	0	0	-1
18/6	0	-1	0
19/6	0	0	1
20/6	0	-1	0
21/6	0	0	-113
22/6	0	0	-117
23/6	0	0	-116
24/6	0	0	-38
25/6	0	0	-64

LC2: SW+Tarp+CS

Stresses		
Bar/Node/Case	S max (MPa)	S min (MPa)
1/1/7	345.43	-335.12
1/2/7	59.49	-49.53
2/2/7	59.49	-49.53
2/3/7	276.25	-266.98
3/3/7	189.56	-183.4
3/4/7	160.78	-155.17
4/5/7	163.78	-158.52
4/6/7	212.86	-208.16
5/6/7	260.85	-254.12
5/7/7	119.7	-113.66
6/7/7	119.7	-113.66
6/8/7	137.65	-131.97
7/10/7	55.93	-46.29
7/9/7	422.94	-413.06
8/5/7	361.15	-351.97
8/10/7	55.93	-46.29
9/3/7	104.68	-99.03
9/5/7	217.16	-211.15
10/4/7	202.97	-199.79
10/6/7	65.99	-62.44
11/11/7	92.63	-86.88
11/4/7	334.75	-328.53
12/12/7	187.11	-181.6
12/11/7	92.63	-86.88
13/13/7	0	0
13/14/7	72.38	-74.99
14/14/7	72.38	-74.99
14/15/7	88.33	-90.94
15/15/7	88.33	-90.94
15/16/7	41.36	-43.97
16/16/7	41.36	-43.97
16/17/7	0	0
17/18/7	84.8	-79.83
17/12/7	139.59	-134.74
18/19/7	86.71	-81.63
18/18/7	84.8	-79.83
19/20/7	88.18	-82.55
19/8/7	198.99	-193.48
20/21/7	148.45	-142.69
20/20/7	88.18	-82.55
21/12/7	-3.46	-3.46
21/1/7	-2.51	-2.51
22/1/7	-9.31	-9.31
22/9/7	-9.13	-9.13
23/8/7	-3.37	-3.37
23/9/7	-2.49	-2.49
24/12/7	-0.06	-0.06
24/22/7	-0.05	-0.05
25/8/7	-0.03	-0.03
25/23/7	-0.02	-0.02

Displacements-Nodes			
Node/Case	UX (mm)	UY (mm)	UZ (mm)
1/6	0	0	0
2/6	8	-27	-36
3/6	0	-53	-92
4/6	-39	-38	-118
5/6	25	-18	-106
6/6	-14	-4	-134
7/6	-28	26	-99
8/6	-17	59	-29
9/6	0	0	0
10/6	17	0	-52
11/6	-34	-8	-78
12/6	-17	52	-25
13/6	-17	58	-21
14/6	-17	36	-50
15/6	-17	41	-66
16/6	-17	54	-51
17/6	-17	59	-23
18/6	1	14	-7
19/6	0	0	0
20/6	-14	15	-7
21/6	0	0	0
22/6	0	0	0
23/6	0	0	0

Deflections- Bars			
Bar/Case	UX (mm)	UY (mm)	UZ (mm)
1/6	0	9	2
2/6	0	-4	-7
3/6	0	-5	2
4/6	0	-5	-2
5/6	0	-8	6
6/6	0	1	1
7/6	0	9	-5
8/6	0	-5	9
9/6	0	-5	2
10/6	0	-5	-2
11/6	0	-7	-8
12/6	0	2	2
13/6	0	-2	-4
14/6	0	-4	0
15/6	0	-3	2
16/6	0	2	1
17/6	0	-3	-4
18/6	0	-4	-1
19/6	0	-4	5
20/6	0	-4	-2
21/6	0	0	-287
22/6	0	0	-326
23/6	0	0	-301
24/6	0	0	-65
25/6	0	0	-156

LC3: SW+Tarp+Wind

Stresses		
Bar/Node/Case	S max (MPa)	S min (MPa)
1/1/6	333.27	-327.79
1/2/6	47.13	-41.72
2/2/6	47.13	-41.72
2/3/6	218.07	-212.74
3/3/6	165.23	-161.86
3/4/6	111.22	-107.93
4/5/6	119.22	-115.14
4/6/6	199.91	-195.91
5/6/6	239.31	-233.77
5/7/6	92.52	-87.06
6/7/6	92.52	-87.06
6/8/6	155.88	-150.48
7/10/6	35.91	-30.01
7/9/6	366.64	-360.69
8/5/6	285.18	-279.33
8/10/6	35.91	-30.01
9/3/6	67.44	-63.97
9/5/6	188.03	-184.51
10/4/6	179.01	-175.81
10/6/6	52.51	-49.27
11/11/6	85.13	-79.86
11/4/6	260.22	-254.9
12/12/6	173.26	-168.04
12/11/6	85.13	-79.86
13/13/6	0	0
13/14/6	65.27	-67.6
14/14/6	65.27	-67.6
14/15/6	87.32	-89.65
15/15/6	87.32	-89.65
15/16/6	36	-38.33
16/16/6	36	-38.33
16/17/6	0	0
17/18/6	75.47	-70.31
17/12/6	163.91	-158.88
18/19/6	76.59	-71.31
18/18/6	75.47	-70.31
19/20/6	75.62	-70
19/8/6	199.21	-193.71
20/21/6	105.47	-99.73
20/20/6	75.62	-70
21/12/6	-3.3	-3.3
21/1/6	-3.21	-3.21
22/1/6	-8.46	-8.46
22/9/6	-8.31	-8.31
23/8/6	-3.35	-3.35
23/9/6	-3.32	-3.32
24/12/6	-0.06	-0.06
24/22/6	-0.04	-0.04
25/8/6	-0.04	-0.04
25/23/6	-0.02	-0.02

Displacements-Nodes			
Node/Case	UX (mm)	UY (mm)	UZ (mm)
1/6	0	0	0
2/6	6	-26	-37
3/6	0	-52	-90
4/6	-26	-44	-111
5/6	17	-27	-98
6/6	-10	-20	-120
7/6	-17	7	-84
8/6	-9	38	-19
9/6	0	0	0
10/6	11	-7	-47
11/6	-23	-15	-71
12/6	-9	40	-19
13/6	-9	45	-16
14/6	-9	19	-41
15/6	-9	15	-55
16/6	-9	28	-40
17/6	-9	40	-12
18/6	5	9	-5
19/6	0	0	0
20/6	-11	7	-4
21/6	0	0	0
22/6	0	0	0
23/6	0	0	0

Deflections- Bars			
Bar/Case	UX (mm)	UY (mm)	UZ (mm)
1/6	0	9	1
2/6	0	-4	-4
3/6	0	-5	1
4/6	0	-5	-1
5/6	0	-8	4
6/6	0	2	0
7/6	0	8	-4
8/6	0	-5	6
9/6	0	-5	1
10/6	0	-5	-1
11/6	0	-7	-6
12/6	0	2	1
13/6	0	-1	-3
14/6	0	-4	-1
15/6	0	-4	1
16/6	0	1	1
17/6	0	-3	-5
18/6	0	-3	1
19/6	0	-4	5
20/6	0	-2	-2
21/6	0	0	-260
22/6	0	149	-274
23/6	0	0	-256
24/6	0	0	-77
25/6	0	0	-122

LC4: SW+Tarp+Snow

Stresses		
Bar/Node/Case	S max (MPa)	S min (MPa)
1/1/6	263.76	-255.68
1/2/6	46.82	-39.02
2/2/6	46.82	-39.02
2/3/6	215.01	-207.73
3/3/6	146.37	-141.53
3/4/6	127.52	-123.1
4/5/6	129.82	-125.65
4/6/6	163.85	-160.09
5/6/6	202.27	-196.89
5/7/6	93.54	-88.69
6/7/6	93.54	-88.69
6/8/6	102.88	-98.3
7/10/6	43.73	-36.15
7/9/6	326.21	-318.45
8/5/6	282.83	-275.6
8/10/6	43.73	-36.15
9/3/6	82.21	-77.76
9/5/6	168.02	-163.3
10/4/6	156.92	-154.35
10/6/6	52.57	-49.73
11/11/6	72.78	-68.15
11/4/6	262.45	-257.47
12/12/6	143.97	-139.52
12/11/6	72.78	-68.15
13/13/6	0	0
13/14/6	56.32	-58.47
14/14/6	56.32	-58.47
14/15/6	69.43	-71.57
15/15/6	69.43	-71.57
15/16/6	32.63	-34.78
16/16/6	32.63	-34.78
16/17/6	0	0
17/18/6	65.76	-61.89
17/12/6	106.12	-102.38
18/19/6	71.64	-67.66
18/18/6	65.76	-61.89
19/20/6	67.98	-63.61
19/8/6	152.55	-148.29
20/21/6	116.78	-112.29
20/20/6	67.98	-63.61
21/12/6	-2.78	-2.78
21/1/6	-2.07	-2.07
22/1/6	-7.49	-7.49
22/9/6	-7.37	-7.37
23/8/6	-2.71	-2.71
23/9/6	-2.06	-2.06
24/12/6	-0.07	-0.07
24/22/6	-0.05	-0.05
25/8/6	-0.03	-0.03
25/23/6	-0.02	-0.02

Displacements-Nodes			
Node/Case	UX (mm)	UY (mm)	UZ (mm)
1/6	0	0	0
2/6	6	-21	-28
3/6	0	-41	-70
4/6	-30	-29	-90
5/6	20	-13	-81
6/6	-11	-2	-103
7/6	-22	22	-77
8/6	-13	46	-23
9/6	0	0	0
10/6	14	1	-40
11/6	-27	-5	-60
12/6	-13	42	-20
13/6	-13	46	-17
14/6	-13	29	-39
15/6	-13	32	-52
16/6	-13	43	-40
17/6	-13	46	-18
18/6	1	11	-5
19/6	0	0	0
20/6	-11	12	-6
21/6	0	0	0
22/6	0	0	0
23/6	0	0	0

Deflections- Bars			
Bar/Case	UX (mm)	UY (mm)	UZ (mm)
1/6	0	7	1
2/6	0	-3	-5
3/6	0	-4	1
4/6	0	-4	-2
5/6	0	-6	5
6/6	0	1	1
7/6	0	7	-4
8/6	0	-4	7
9/6	0	-4	1
10/6	0	-3	-1
11/6	0	-5	-7
12/6	0	1	2
13/6	0	-1	-3
14/6	0	-3	0
15/6	0	-3	1
16/6	0	1	1
17/6	0	-2	-3
18/6	0	-3	0
19/6	0	-3	4
20/6	0	-3	-2
21/6	0	0	-257
22/6	0	0	-294
23/6	0	0	-268
24/6	0	0	-62
25/6	0	0	-139

LC5: SW+Tarp+Wind+CS		
Stresses		
Bar/Node/Case	S max (MPa)	S min (MPa)
1/1/6	622.27	-609.3
1/2/6	89.21	-76.6
2/2/6	89.21	-76.6
2/3/6	425.94	-414.02
3/3/6	315.12	-307.34
3/4/6	219.91	-212.69
4/5/6	228.93	-221.43
4/6/6	370.96	-364
5/6/6	441.31	-431.5
5/7/6	181.16	-172.04
6/7/6	181.16	-172.04
6/8/6	282.34	-273.57
7/10/6	76.57	-63.87
7/9/6	701.77	-688.84
8/5/6	547.41	-535.18
8/10/6	76.57	-63.87
9/3/6	141.03	-133.6
9/5/6	357.4	-349.61
10/4/6	338.97	-333.9
10/6/6	94.82	-89.39
11/11/6	151.39	-142.63
11/4/6	504.11	-494.89
12/12/6	327.38	-318.86
12/11/6	151.39	-142.63
13/13/6	0	0
13/14/6	120.76	-124.36
14/14/6	120.76	-124.36
14/15/6	154.26	-157.87
15/15/6	154.26	-157.87
15/16/6	65.36	-68.97
16/16/6	65.36	-68.97
16/17/6	0	0
17/18/6	141.03	-131.89
17/12/6	288.39	-279.37
18/19/6	123.58	-114.32
18/18/6	141.03	-131.89
19/20/6	144.99	-134.86
19/8/6	366.68	-356.67
20/21/6	212.74	-202.5
20/20/6	144.99	-134.86
21/12/6	-5.39	-5.39
21/1/6	-4.39	-4.39
22/1/6	-13.98	-13.98
22/9/6	-13.61	-13.61
23/8/6	-5.25	-5.25
23/9/6	-4.43	-4.43
24/12/6	-0.05	-0.05
24/22/6	-0.04	-0.04
25/8/6	-0.03	-0.03
25/23/6	-0.02	-0.02

Displacements-Nodes			
Node/Case	UX (mm)	UY (mm)	UZ (mm)
1/6	0	0	0
2/6	11	-48	-68
3/6	0	-97	-168
4/6	-53	-80	-209
5/6	34	-48	-185
6/6	-19	-32	-228
7/6	-36	20	-161
8/6	-22	80	-39
9/6	0	0	0
10/6	23	-11	-89
11/6	-47	-26	-133
12/6	-22	74	-36
13/6	-22	83	-28
14/6	-22	41	-78
15/6	-22	41	-104
16/6	-22	64	-78
17/6	-22	82	-28
18/6	6	17	-8
19/6	0	0	0
20/6	-23	16	-8
21/6	0	0	0
22/6	0	0	0
23/6	0	0	0

Deflections- Bars			
Bar/Case	UX (mm)	UY (mm)	UZ (mm)
1/6	0	16	2
2/6	0	-8	-9
3/6	0	-10	2
4/6	0	-9	-3
5/6	0	-14	9
6/6	0	3	1
7/6	0	16	-7
8/6	0	-9	13
9/6	0	-9	2
10/6	0	-9	-2
11/6	0	-13	-11
12/6	0	4	3
13/6	0	-2	-5
14/6	0	-7	-1
15/6	0	-6	2
16/6	0	2	2
17/6	0	-6	-8
18/6	0	-5	1
19/6	0	-8	9
20/6	0	-5	-4
21/6	0	0	-345
22/6	0	93	-383
23/6	0	0	-356
24/6	0	0	-81
25/6	0	0	-177

LC6: SW+Tarp+Snow+CS		
Stresses		
Bar/Node/Case	S max (MPa)	S min (MPa)
1/1/6	554.46	-538.61
1/2/6	90.71	-75.42
2/2/6	90.71	-75.42
2/3/6	429.3	-415.14
3/3/6	298.67	-289.25
3/4/6	241.67	-233.14
4/5/6	246.1	-238.24
4/6/6	337.12	-330.16
5/6/6	408.1	-398.12
5/7/6	185.07	-176.22
6/7/6	185.07	-176.22
6/8/6	228.06	-219.77
7/10/6	86.18	-71.5
7/9/6	667.66	-652.6
8/5/6	555.15	-541.23
8/10/6	86.18	-71.5
9/3/6	159.97	-151.39
9/5/6	341.11	-331.92
10/4/6	319.43	-314.81
10/6/6	98.01	-92.79
11/11/6	141.67	-133.25
11/4/6	514.1	-504.94
12/12/6	297.69	-289.65
12/11/6	141.67	-133.25
13/13/6	0	0
13/14/6	113	-116.65
14/14/6	113	-116.65
14/15/6	137.37	-141.01
15/15/6	137.37	-141.01
15/16/6	63.35	-66.99
16/16/6	63.35	-66.99
16/17/6	0	0
17/18/6	132.67	-124.84
17/12/6	227.83	-220.12
18/19/6	121.48	-113.53
18/18/6	132.67	-124.84
19/20/6	139.17	-130.28
19/8/6	319.47	-310.69
20/21/6	228.08	-219.07
20/20/6	139.17	-130.28
21/12/6	-5.06	-5.06
21/1/6	-3.47	-3.47
22/1/6	-13.5	-13.5
22/9/6	-13.16	-13.16
23/8/6	-4.87	-4.87
23/9/6	-3.44	-3.44
24/12/6	-0.06	-0.06
24/22/6	-0.05	-0.05
25/8/6	-0.03	-0.03
25/23/6	-0.02	-0.02

Displacements-Nodes			
Node/Case	UX (mm)	UY (mm)	UZ (mm)
1/6	0	0	0
2/6	12	-44	-59
3/6	0	-86	-149
4/6	-58	-64	-189
5/6	38	-32	-169
6/6	-21	-12	-212
7/6	-42	37	-156
8/6	-27	90	-44
9/6	0	0	0
10/6	26	-2	-82
11/6	-52	-16	-123
12/6	-27	77	-37
13/6	-27	86	-31
14/6	-27	53	-77
15/6	-27	60	-102
16/6	-27	81	-78
17/6	-27	91	-34
18/6	1	19	-9
19/6	0	0	0
20/6	-23	22	-11
21/6	0	0	0
22/6	0	0	0
23/6	0	0	0

Deflections- Bars			
Bar/Case	UX (mm)	UY (mm)	UZ (mm)
1/6	0	14	2
2/6	0	-7	-10
3/6	0	-8	3
4/6	0	-8	-3
5/6	0	-13	9
6/6	0	2	2
7/6	0	14	-8
8/6	0	-8	14
9/6	0	-8	3
10/6	0	-7	-3
11/6	0	-11	-12
12/6	0	3	3
13/6	0	-3	-6
14/6	0	-6	0
15/6	0	-5	3
16/6	0	2	2
17/6	0	-5	-7
18/6	0	-5	-1
19/6	0	-7	8
20/6	0	-6	-4
21/6	0	0	-346
22/6	0	0	-388
23/6	0	0	-368
24/6	0	0	-68
25/6	0	0	-190

LC7: SW+Tarp+Wind+CS+Snow		
Stresses		
Bar/Node/Case	S max (MPa)	S min (MPa)
1/1/6	829.48	-811.27
1/2/6	118.6	-100.96
2/2/6	118.6	-100.96
2/3/6	572.92	-556.41
3/3/6	421.67	-410.82
3/4/6	294.63	-284.68
4/5/6	304.38	-294.52
4/6/6	492.79	-483.82
5/6/6	584.27	-571.55
5/7/6	243.8	-232.2
6/7/6	243.8	-232.2
6/8/6	373.97	-362.94
7/10/6	105.2	-87.78
7/9/6	940.74	-922.95
8/5/6	731.44	-714.78
8/10/6	105.2	-87.78
9/3/6	192.56	-182.39
9/5/6	477.94	-467.17
10/4/6	452.88	-446.57
10/6/6	123.49	-116.59
11/11/6	197.7	-186.61
11/4/6	675.11	-663.26
12/12/6	437.96	-427.24
12/11/6	197.7	-186.61
13/13/6	0	0
13/14/6	160.37	-164.78
14/14/6	160.37	-164.78
14/15/6	203.24	-207.64
15/15/6	203.24	-207.64
15/16/6	86.59	-91
16/16/6	86.59	-91
16/17/6	0	0
17/18/6	187.38	-175.37
17/12/6	379.23	-367.34
18/19/6	154.83	-142.69
18/18/6	187.38	-175.37
19/20/6	194.45	-181.06
19/8/6	488.04	-474.77
20/21/6	289.83	-276.32
20/20/6	194.45	-181.06
21/12/6	-6.76	-6.76
21/1/6	-5.12	-5.12
22/1/6	-17.66	-17.66
22/9/6	-17.1	-17.1
23/8/6	-6.51	-6.51
23/9/6	-5.14	-5.14
24/12/6	-0.05	-0.05
24/22/6	-0.04	-0.04
25/8/6	-0.03	-0.03
25/23/6	-0.01	-0.01

Displacements-Nodes			
Node/Case	UX (mm)	UY (mm)	UZ (mm)
1/6	0	0	0
2/6	15	-64	-91
3/6	0	-129	-224
4/6	-71	-106	-278
5/6	46	-64	-247
6/6	-25	-42	-305
7/6	-50	28	-216
8/6	-32	109	-53
9/6	0	0	0
10/6	32	-13	-118
11/6	-64	-35	-177
12/6	-32	96	-47
13/6	-32	108	-37
14/6	-32	56	-104
15/6	-32	58	-139
16/6	-32	89	-104
17/6	-32	111	-38
18/6	7	22	-11
19/6	0	0	0
20/6	-31	23	-11
21/6	0	0	0
22/6	0	0	0
23/6	0	0	0

Deflections- Bars			
Bar/Case	UX (mm)	UY (mm)	UZ (mm)
1/6	0	22	3
2/6	0	-10	-12
3/6	0	-13	3
4/6	0	-13	-4
5/6	0	-19	11
6/6	0	4	2
7/6	0	21	-10
8/6	0	-12	17
9/6	0	-12	3
10/6	0	-11	-3
11/6	0	-17	-15
12/6	0	5	4
13/6	0	-3	-7
14/6	0	-10	-1
15/6	0	-8	3
16/6	0	3	2
17/6	0	-8	-11
18/6	0	-6	-1
19/6	0	-11	12
20/6	0	-7	-5
21/6	0	0	-391
22/6	0	75	-433
23/6	0	0	-410
24/6	0	0	-80
25/6	0	0	-205

10 Appendix B- Additional Computational Results

Results obtained from the remaining models in Autodesk Robot are contained in the accompanying cd.