# CHAPTER 1 - PROJECT INTRODUCTION

## 1.0 INTRODUCTION:

On 12th January 2010 at 16:53, an earthquake rated at 7.0 on the Richter Scale occurred on the Caribbean Republic of Haiti, with an epicentre 13km from its densely populated capital, Port Au Prince. Whilst the quake was not as large as those occurring in other parts of the world, the desperate state of the country's economy and resulting lack of building codes resulted in a catastrophic destruction of the building stock and a death toll close to 217,000 and rising (M.Hearty 2010: 36), making it one of the worst natural disasters ever recorded.

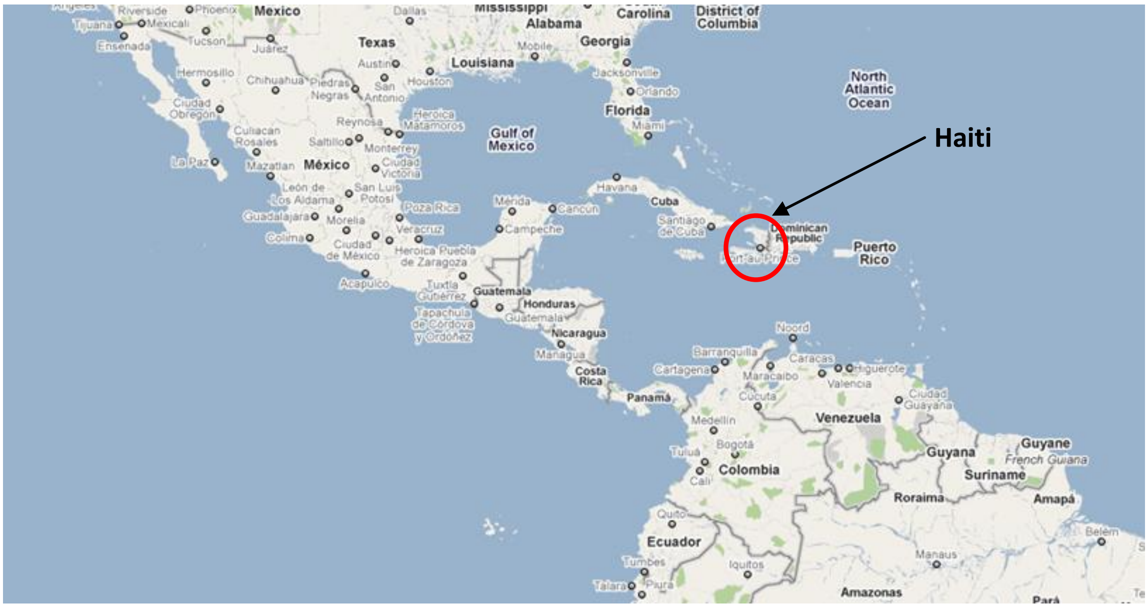


**Fig 1.0.1:** Location of Haiti in the Caribbean (Google Map)

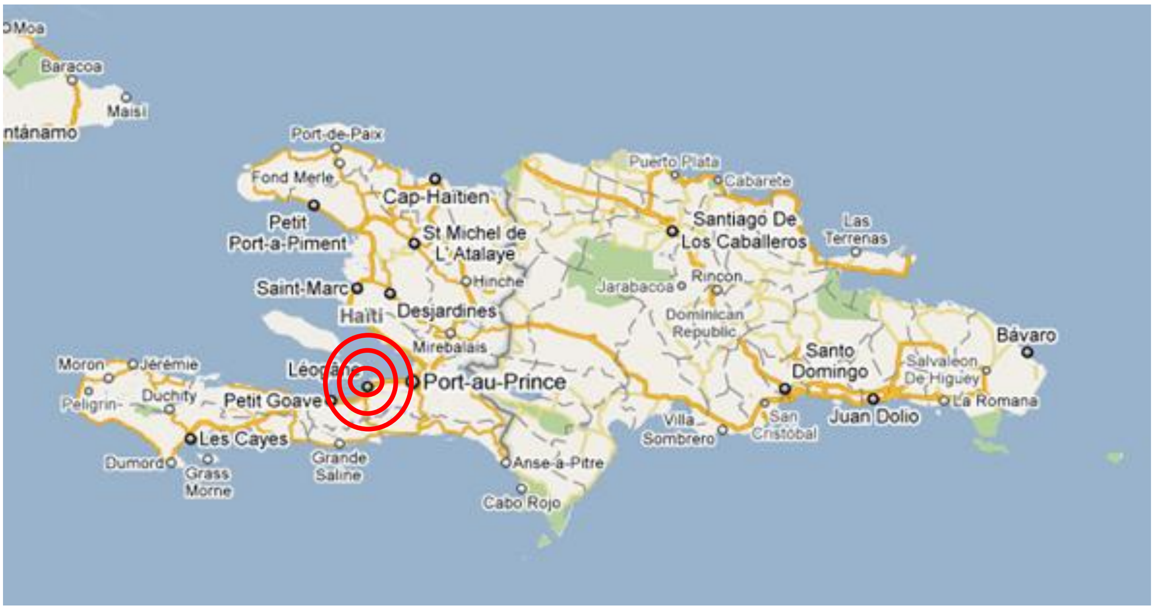


**Fig 1.0.2:** Arial Map of Haiti and Dominican Republic - Indicating Location of Earthquake Epicentre (Google Map)

In the aftermath of the quake, the social and economic problems in Haiti are worsening and it is estimated that 6 months on, there remains up to 1 million people with no access to shelter at all (M.Hearty 2010: 36). In disaster situations, many researchers and agencies such as Giepel (1991) and the United Nations Disaster Relief Organisation (1982), believe that the reconstruction of communities in the form of *transitional* shelter settlements underpin the physical, social and economic reconstruction process. Da Silva describes the term of transitional shelter as 'bridging the gap between emergency measures and durable housing, which is a human right under Article 25(1) , Universal Declaration of Human Rights, 1948' (Da Silva 2007:P26).

The 'Hexayurt' is a transitional shelter concept by Vinay Gupta, with the intended advantages of material availability, constructability and low cost.

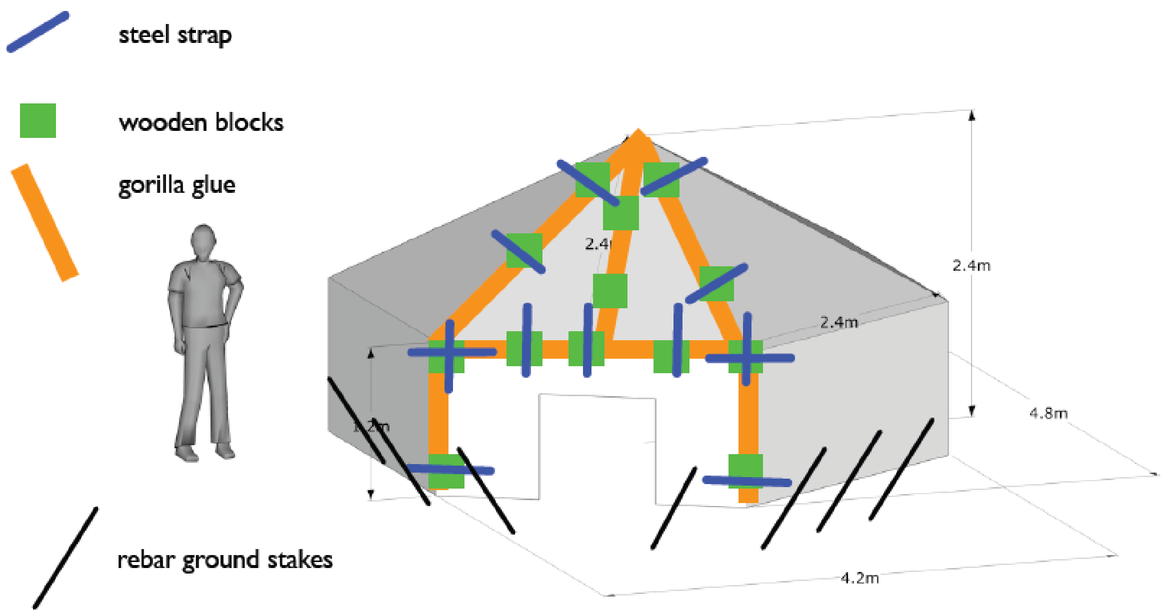


**Fig 1.0.3:** The Hexayurt Concept (Gupta: 2)

At the time of the Haiti earthquake, The Hexayurt shelter project remained relatively undeveloped for use in an environment such as Haiti, it was initially constructed out of lightweight insulation board for use in much more stable climates. However, the desperate need for a solution in Haiti has prompted Gupta to attempt to adapt the design to a more durable unit, capable of withstanding tropical storms experienced during certain months in the calendar.

In the initial feasibility study document 'The Hexayurt in Haiti?', Gupta has identified 4 questions which much be answered before the Hexayurt could be deployed in Haiti:

1. Will the building stand up to wind, snow and other structural factors?

2. For a given material, how long will it last in the climate? What is the best material in terms of price/performance?

3. How will the building be connected to the ground?

Once these questions are answered, the building becomes an operational option, if:

4. We have a sign off from an engineer that this looks reasonable.

(Gupta 2010:P16)

It is clear that it is beyond the scope of a single research project to determine these factors. Hence, in light of my own personal experience and interest it is appropriate for me to attempt to answer question 1.

## 1.1 AIMS, OBJECTIVES & HYPOTHESES:

The aims and objectives of this project have been developed on the basis that no previous analysis or testing have been carried out on the Hexayurt. For that reason, they remain reasonably broad. It is desired that this project will provide scope for further more concise research projects for the future.

**Aim:**

This translates to define the aim of this research project, to quantitatively assess the structural adequacy of the 'Hexayurt' for use as a transitional disaster relief shelter in Haiti.

**Objectives:**

Whilst the aim remains a broad overview of what will desirably be achieved, there are several objectives which define the project, thus providing scope. The objectives are as follows:

1. Analyse the environmental conditions specific to Haiti (climatic, seismic and geographical) in order to facilitate the development of a safe and adequate solution.

2. Assess the structural performance using building code standards of the 'un-engineered' existing design in the specific environment of Haiti. Developing an understanding of how the building works structurally in its current form will allow potential areas of structural weakness to be identified and subsequently developed to optimise the design.

Sub-Objective 2i) Since it is possible to identify that constructability will form an integral part of the success of the hexayurt, there is a need to determine the most appropriate joint arrangement to aid the constructability of the unit in the field.

3. Use the identification of areas of structural weakness to carry out physical testing, in order to corroborate the data from the assessment and prove the stability of the hexayurt.

4. From research conducted, make recommendations for areas of further research to refine the design of the Hexayurt.

**Hypotheses:**

From the aims and objectives identified, it follows that there is one main hypothesis and one sub-hypothesis:

Main Hypothesis:

'The existing structural form of the Hexayurt is adequate to withstand the environment of Haiti'

Sub Hypothesis:

'The structural form can be modified in order to utilise only screwed joints made from CLS (Canadian Lumber Standard) Timber'

# CHAPTER 2: BACKGROUND

## 2.0 HAITI, SETTING THE SCENE:

The Republic of Haiti forms the western third of the island of Hispaniola; the second largest of the Caribbean islands, positioned approximately 80km South-East of Cuba in the Caribbean Sea. Hispaniola has a total land area of 76,480 km², with Haiti occupying 27,500 km² (McIntosh (2000: 88)). As of 2004, the population of Haiti was 8.67million (World of Information (2006: 270)).

According to the United Nations Human Development Index, Haiti is the poorest country in the western hemisphere, and one of the poorest overall in the world; with a nominal GDP of US $7.018 billion in 2009 which represents a per capita amount of US $790 annually or US $2 per person per day (United Nations (2009)). This translates to 80% of the population living below the poverty line (World of Information (2006: 203)). Years of conflict, political instability and recurrent natural disasters such as cyclones, floods and mudslides have stifled economic progression and weakened Haiti's already low capacity to invest in the long term safety of its citizens. In 2004, the national debt stood at US $1.2bn, and according to World of Information (2006: 207-273), a history of political corruption has rendered Haiti ineligible for aid initiatives such as the Heavily Indebted Poor Countries (HIPC) fund introduced by the IMF in 1999.

The illiteracy rate in Haiti stands at 50% aged 15 years, according to the World Bank, and just 40% of the population has access to basic health care, resulting in an average life expectancy of 61. This fairs it much worse off when compared with its neighbour the Dominican Republic, where the figures stand at 87%, 82% and 71 years respectively (World of Information (2006: 273)).

Haiti's social and economic average trend indicators remain lower than the average for Latin America and the Caribbean. Aside from the traditional food processing, construction and textile industries, Haiti has an important artesian manufacturing sector producing handicrafts, the majority of which are exported. Many US owned-light manufacturing and assembly plants also operate within Haiti, as labour rates are vastly cheaper than in the USA, where workers are typically paid US $2-3 per day. Overall, little of the output is produced for local consumption and the majority is exported to wealthier economies, (World of Information (2006: 271)). With regards to the country's natural resources, Malik (1989: 46) observes how the reoccurrence of natural disasters, along with the need to generate income through the exporting of raw materials has led to widespread, uncontrolled deforestation.

Haiti's capital Port Au Prince, where the country's main seaport and only airport are situated, is a densely populated space which is home to up to 1.2 million people. Poor welfare provision into rural areas has attracted ever increasing numbers to the already overly populated the capital. The need for rapid, low cost urban expansion, has inevitably lead to compromised settlement sites and poor building practise, raising the risk of disaster in natural hazard zones (Rathje 2010).

## 2.1 THE CLIMATE IN HAITI:

### 2.1.1 Overview

Typical of equatorial regions, Haiti is essentially a tropical climate. That is to say that there exists a constant air temperature of greater than 18˚C, with medium to high levels of humidity and an annual or bi-annual period of considerable precipitation (McKnight, Tom L; Hess, Darrel (2000)). Additionally, extreme wind speeds and occasionally hurricanes occur in Haiti. These are in the main induced by the tropical storms and severe thunder storms during the rainy seasons.

To contribute to the problems in Haiti, the tropical climate and rainy seasons set to further stifle the reconstruction process, as identified and investigated by Adams (2010). Adams (2010: 1067) describes how the season could rapidly increase the spread of potentially fatal disease, in particular within the many un-sheltered communities. This provides further urgent justification for an acceptable shelter solution to be deployed.

As identified by Gupta in the paper 'Hexayurt in Haiti?' (Gupta 2010: 7), the climate conditions with respect to moisture (from humidity and precipitation), and wind in Haiti are crucial considerations in achieving a successful, adequate and safe design for the hexayurt.

### 2.1.2 Specific Climate Data

Pearce and Smith (2000: 170) have published climate data for the capital Port au Prince, in The Hutchinson World Weather Guide (see fig 4.2.1 and 4.2.2). The data based on readings for 42 years taken from a weather station based at 18˚33' N W, altitude 37m 121cm above sea level.

| **Sunshine Ave. Hours per Day** | | **Temperatures** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Average Daily | | | | Highest Recorded | | Lowest Recorded | |
| | | Minimum | | Maximum | | | | | |
| | | C | F | C | F | C | F | C | F |
| Jan | 9 | 20 | 68 | 31 | 87 | 34 | 93 | 17 | 62 |
| Feb | 9 | 20 | 68 | 31 | 88 | 35 | 95 | 16 | 61 |
| Mar | 9 | 21 | 69 | 32 | 89 | 37 | 98 | 16 | 60 |
| Apr | 9 | 22 | 71 | 32 | 89 | 37 | 98 | 16 | 61 |
| May | 8 | 22 | 72 | 32 | 90 | 37 | 99 | 1 | 66 |
| Jun | 8 | 23 | 73 | 33 | 92 | 37 | 99 | 19 | 66 |
| Jul | 9 | 23 | 74 | 34 | 94 | 38 | 101 | 19 | 67 |
| Aug | 9 | 23 | 73 | 34 | 93 | 38 | 101 | 20 | 68 |
| Sep | 8 | 23 | 73 | 33 | 91 | 37 | 99 | 19 | 67 |
| Oct | 8 | 22 | 72 | 32 | 90 | 37 | 98 | 19 | 66 |
| Nov | 7 | 22 | 71 | 31 | 88 | 36 | 96 | 18 | 64 |
| Dec | 7 | 21 | 69 | 31 | 87 | 34 | 93 | 16 | 60 |

**Fig 2.1.2.1:** Temperature Data for Port Au Prince

| Discomfort from heat and humidity | Precipitation and Humidity | | | | Wet Days more than 1mm/0.04in | |
|---|---|---|---|---|---|---|
| | Relative Humidity | | Ave. Monthly Precipitation | | | |
| | 07:00 | 13:00 | | | | |
| | % | | mm | in | | |
| Medium | 71 | 44 | 33 | 1.3 | 3 | Jan |
| Medium | 71 | 44 | 58 | 2.3 | 5 | Feb |
| Medium | 70 | 45 | 86 | 3.4 | 7 | Mar |
| High | 71 | 49 | 160 | 6.3 | 11 | Apr |
| High | 75 | 54 | 231 | 9.1 | 13 | May |
| High | 71 | 50 | 102 | 4 | 8 | Jun |
| High | 68 | 43 | 74 | 2.9 | 7 | Jul |
| High | 72 | 49 | 145 | 5.7 | 11 | Aug |
| High | 76 | 54 | 175 | 6.9 | 12 | Sep |
| High | 79 | 56 | 170 | 6.7 | 12 | Oct |
| Medium | 77 | 54 | 84 | 3.4 | 7 | Nov |
| Medium | 73 | 48 | 33 | 1.3 | 3 | Dec |

**Fig 2.1.2.2:** Precipitation and Humidity Data for Port Au Prince

## 2.2 WIND SPEED DATA:

Specific wind speed data for the Caribbean as a whole is in short supply, which is not surprising given the minimal building codes developed for the region. Granger (1985) has produced a paper called 'Caribbean Climates', which has provided guidance in achieving an informed estimate wind speed for the Haitian environment.

Fig 2.2.1 lists worst case wind speed data for various countries in the Caribbean, excluding Haiti. Given Grainger's assessment of the Jamaican climate being similar to that of Haiti, and their close geographical proximity, a value of 38 m/s worst case wind speed will be used for the design of the hexayurt.

| Location | Return Periods | | | | | |
|---|---|---|---|---|---|---|
| | 10 Years | | 50 Years | | 100 Years | |
| | a | b | a | b | a | b |
| Palisadoes, Jamaica | 32 | 38 | 42 | 49 | 47 | 55 |
| Coolidge, Antigua | 35 | 42 | 46 | 54 | 51 | 59 |
| Seawell, Barbados | 35 | 42 | 45 | 52 | 49 | 57 |
| Pearls, Grenada | 30 | 36 | 38 | 45 | 42 | 50 |
| Piarco, Trinidad | 21 | 27 | 28 | 34 | 31 | 37 |
| Crown Point, Tobago | 30 | 36 | 38 | 45 | 42 | 49 |

a: Maximum Mile Speed (m/s)

b: Maximum 3 Second Gust Speed (m/s)

**Fig 2.2.1:** Wind Speed Data for Various Caribbean Countries (Granger (1985))

## 2.3 2010 EARTHQUAKE & SEISMIC SETTING:

The recent earthquake in Haiti, rated at 7.0 on the Richter Scale, struck on 12th January 2010 at 16:53 local time, with an epicentre approximately 13km from the densely populated capital, Port Au Prince.

Haiti is positioned on the boundary between the Gonave Micro and Caribbean tectonic plates, with the Enriquillo-Plantain Garden fault which separates the plates running directly through Port Au Prince, heading west through the capital of Jamaica, Kingston. The New York Times has identified that the Enriquillo-Plantain Garden fault has shown a previous period of earthquake activity in that region (see fig 2.3.1).

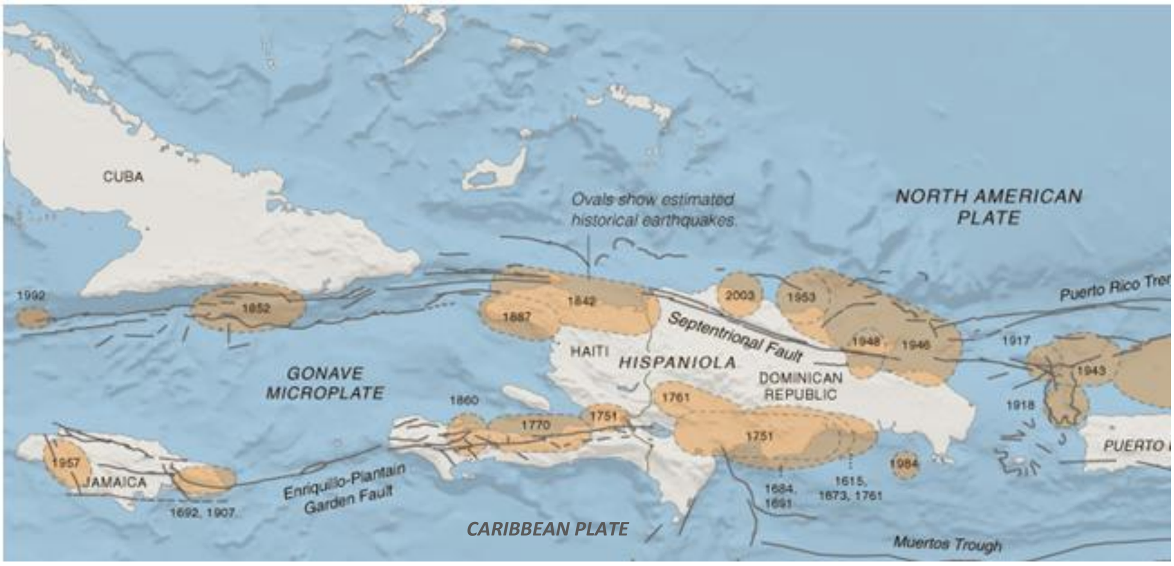


**Fig 2.3.1:** Arial map showing locations of tectonic plates, faults and previous earthquakes (with year of occurrence) in the region of Hispaniola.

(New York Times 2010)

A fault is a fracture, or discontinuity in a volume of rock. In the case earthquake formation, the discontinuity exists through the earth's crust. Faults are present across the planet, which results in a series of free moving crustal plates, known as tectonic plates, to systematically move past each other. This movement is caused by convection currents in the mantle beneath, driven by the heat at the earth's core. The interaction between tectonic plates at fault zones is the root cause of vibration waves which result in tsunamis and earthquakes (Yeats et al (1997:9-15)).

The plates behave in various ways at faults, and can hence be categorised. The Enriquillo-Plantain Garden fault is a 'strike slip fault', meaning that plates are laterally moving past each other, in this case at the rate of 20mm per year (Fierro and Perry (2010: 3)). This results in the development of a huge amount of strain energy. When the critical stress is developed to overcome the friction between the two plates, strain energy acquired in the plates is suddenly released causing large displacements, and in doing so induces waves leading to an earthquake or tsunami. In the case of Haiti, 259 years of strain since the previous earthquake in that section of the fault was released in 60 seconds causing displacement of up to 1.0m (Rathje (2010))

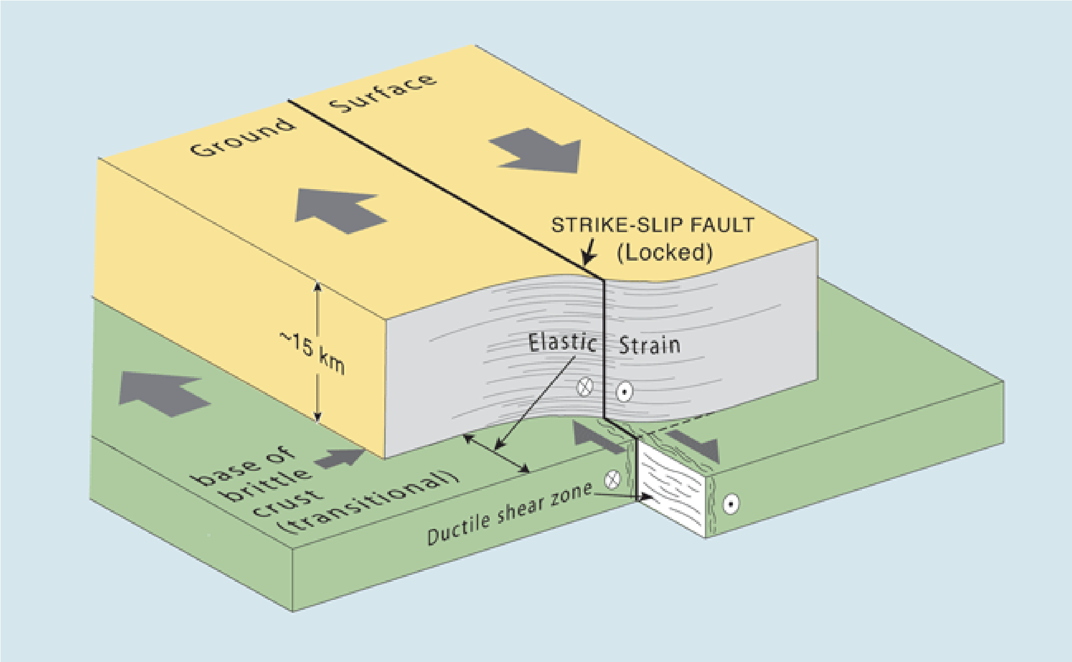


**Figure 2.3.2**: Diagrammatic Representation of a 'Strike Slip Fault'

(San Francisco State University)

Crucially, this sudden release in one area of a tectonic fault *can* result in energy transfer to a different part of the fault and hence lead to a sudden increase in strain energy, dramatically increasing the risk of another quake elsewhere along the fault. Professor Paul Mann from the University of Texas (Channel 4 (2010)), believes that the history of the Enriquillo-Plantain Garden fault shows that the earthquake in January 2010 was merely the beginning of an intense period of activity; similar to the period of activity in the 1700's, which saw 3 earthquakes occur in 19 years or the 1600's which saw 4 earthquakes occur in 76 years (see Fig 2.3.1). Scientists such as Mann believe that this makes a second earthquake 'at best a strong possibility'.

This has an obvious implication on the design of the Hexayurt, that its design life must be longer to cater for a potentially extended reconstruction period; and it must offer a degree of resistance to future seismic activity.

# CHAPTER 3 - POST EARTHQUAKE HAITI TO JULY 2010

## 3.1 SCALE OF THE DISASTER

The earthquake of January 12th 2010 in Haiti was one of the worst natural disasters ever recorded, both in terms of loss of life and physical damage. The table below (fig 3.1.1) by Cavallo, Powell and Becerra of the Inter-American Development Bank, represents 10 previous natural disasters in relation to Haiti and grades them in deaths per million inhabitants. Also shown in the table is total number of people killed, damages in US $ millions and damages as a percentage of GDP. The scale of this disaster is demonstrated as Haiti is at the top of the table in all categories.

| Country (In Rank Order) | Year | Description | People Killed | People Killed Per Million Inhabitants | Damages (US Millions, 2009) | Damages (% of GDP) |
|---|---|---|---|---|---|---|
| Haiti | 2010 | Earthquake | 150,000 - 200,000 | 15,000 - 25,000 | 7,200 - 8,100 | 104 - 117 |
| 1.Nicaragua | 1972 | Earthquake | 10,000 | 4,046 | 4,325 | 102.0 |
| 2.Guatamala | 1976 | Earthquake | 23,000 | 3,707 | 3,725 | 27.4 |
| 3.Myanmar | 2008 | Cyclone Nagris | 138,366 | 2,836 | 4,113 | N/A |
| 4.Honduras | 1974 | Cyclone Fifi | 8,000 | 2,733 | 2,263 | 59.2 |
| 5.Honduras | 1998 | Cyclone Mitch | 14,600 | 2,506 | 5,020 | 81.4 |
| 6.Sri Lanka | 2004 | Tsunami* | 35,405 | 1,839 | 1,494 | 7.0 |
| 7.Venezuela | 1999 | Flood | 30,005 | 1,282 | 4,072 | 3.5 |
| 8.Bangladesh | 1991 | Cyclone Gorki | 139,252 | 1,232 | 3,038 | 6.4 |
| 9.Solomon Is. | 1975 | Tsunami | 200 | 1,076 | N/A | N/A |
| 10.Indonesia | 2004 | Tsunami* | 165,825 | 772 | 5,197 | 2.4 |

*Indian Ocean Tsunami caused a total of 226,000 deaths over 12 countries

N/A: Not Available

**Fig 3.1.1:** Table Showing Large World Wide Natural Disasters and Damage Sustained

(Inter-American Development Bank)

The IDB report (Cavallo, Powell & Becerra: 2010) estimates a direct economic damage of the earthquake to be in the order of US $8.1bn and US $13.9bn. Perhaps more significantly, the report notes how 10 years after a disaster of this magnitude occurs, the affected country's growth may be as much as 30% lower than it may have otherwise been, even in light of significant increase in aid provision. This further demonstrates the long term consequences of the earthquake for Haiti, which was already one of the world's poorest countries, and further highlights the need for a durable shelter solution.

## 3.2 CAUSES OF DISASTER

Several factors combined, created the catastrophic scale of destruction in the aftermath of the Haiti earthquake. The first being the location of the Enriquillo-Plantain Garden fault, which runs almost directly through the capital, Port au Prince. The epicentre occurred just 15km from the capital, at depth of 13km below ground level, which, according to Prof Rathje (2010) is comparatively shallow. In brief, this results in a higher concentration of 'surface waves', the most destructive of the waves formed during earthquake activity. They are formed close to the epicentre and only able to travel through the outer part of the Earth's crust. The waves force the ground to move in a circular motion, causing it to rise and fall as visible waves move across the ground (Yeats et al (1997:62)).

The USGS has published seismic instrumental intensity estimates from its shakemap programme (fig 3.2.1). The map shows how the southern region in the area of Port Au Prince represents the greatest shaking with a peak ground velocity of >116cm/second. Whilst damage is heavily dependent on geological conditions, the map can be used as a rough guide to levels of physical damage, injury and death, as well as likely zones of high displacement of the population.

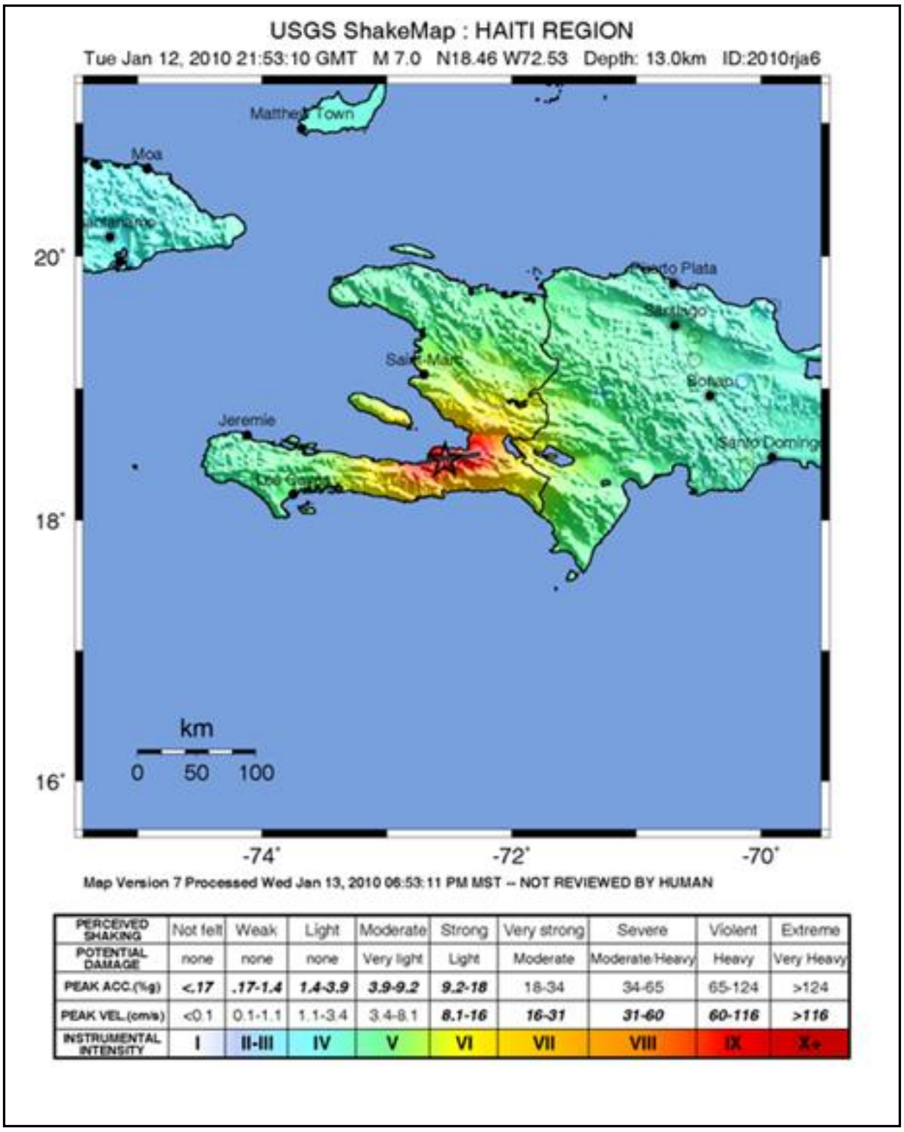


**Fig 3.2.1:** USGS 'Shakemap'; Haiti Earthquake, January 2010

Secondly, the geological conditions of the epicentral region exacerbated the effect of the quake. Both Fierro & Perry (2010: 7), and McGuire (2010) observed a marked difference in degrees of damage and disturbance during field visits following the quake. Landslides (in part as a result of widespread deforestation) and rock falls were commonplace on hillsides surrounding Port-au-Prince, subsequently blocking roads and bringing down communication and power lines. Evidence of liquefaction and lateral spreading in the port area, resulted also in the collapse of marine structures. This provided key evidence that varying ground conditions attributed to varying levels and types of damage. Following further research by Professor Bill McGuire of UCL hazard research centre (Channel 4 (2010)), it was discovered that areas of increased damage were either on 'made-ground' or sedimentary soil types, which are prone to liquefaction when subjected to vibration and cause 'amplification' of seismic waves.

Finally, and perhaps most prominently, Port Au Prince is a particularly densely populated and poor city. Poor urban planning has resulted in a city with sprawling districts, typically made up of 80-90% un engineered buildings (Prof. Ellen Rathje (2010)). Researchers in the field following the quake such as Rathje and Fierro & Perry (2010: 4), have reported a 'complete absence of seismic detailing' in Haitian construction, from informal housing to recent multi-storey buildings in downtown Port-au-Prince. There is no building code in Haiti and no licensing requirements for engineers, architects or contractors. It understood that the majority of the small amount of buildings constructed to developed codes were designed based on the French code (Beton Arme aux Etats Limites), which has no provisions for seismic design (Fierro & Perry (2010: 6)). Surviving witnesses reported the 'pancake effect' failure of multi-storey buildings, as lack of strength at connections and little or no redundancy resulted in floors crashing down on top of each other like a failing pyramid of cards (Channel 4 (2010)). This is a direct result of the largely 'top heavy' brittle and weak design of the building stock in a Haiti

**Fig 3.2.2:** Unfinished Building Showing 'Pancake' Style Failure; Fierro & Perry (2010)

Failure at 1st floor. Few transverse walls, heavy floors and undersized, weak columns. Complete lack of ductile detailing.

**Fig 3.2.3:** Unfinished Building Failure Fierro & Perry (2010)

**Fig 3.2.4:** Collapse of Concrete Column With Minimal Reinforcement; Fierro & Perry (2010)

Disasters, particularly those in developing countries, tend to follow an all too familiar pattern. Lizarralde et al (2010: 4) have identified the causes of a hazard becoming disaster from the Turkey earthquake of 1999. The review of the causes of disaster from this chapter show that the same principles can be applied to Haiti in 2010.

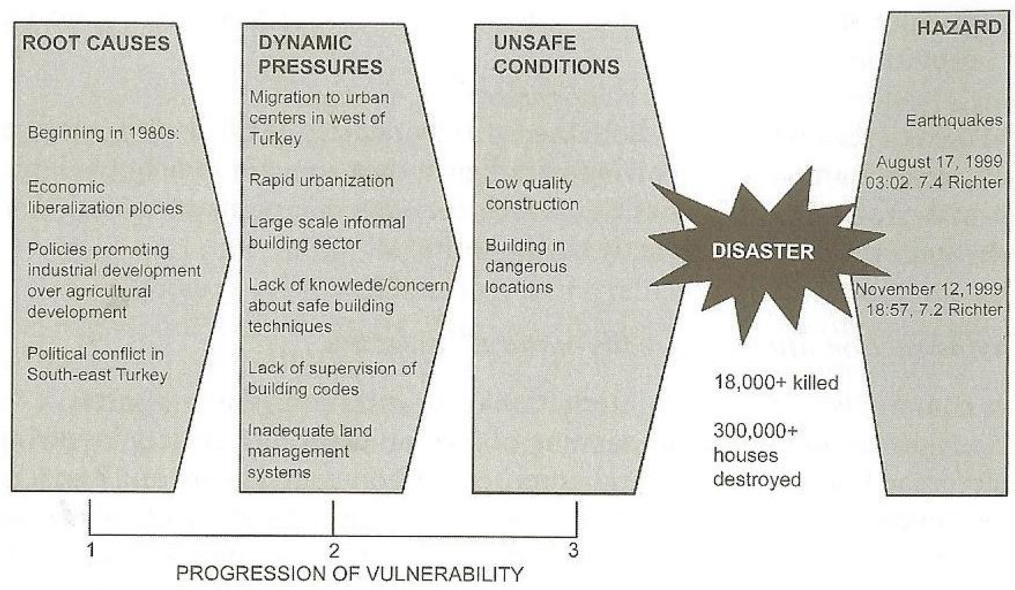


**Fig 3.2.5:** The Development of the Turkey Earthquake Disaster 1999 (Lizarralde et al (2010))

## 3.3 HUMANITARIAN RESPONSE TO DATE

Fierro and Perry (2010:10) describe how the severe damage to roads, ports and airports caused by the earthquake, together with the loss of existing humanitarian aid workers and supplies already in place in Haiti, led to a difficult and slow start to the relief efforts. On the 14th January, two days following the quake, they noted the absence of any kind of assistance to affected civilians. No search and rescue teams, police or military, cleanup crews, heavy equipment or food stations and no temporary sanitation network. It can be said with some certainty that this resulted in many preventable deaths. Taylor (2010: 25-42) describes how the international humanitarian community was heavily criticised in the press for the speed of deployment, but emphasises the multitude of mitigating factors in a disaster of the scale and complexity of Haiti. As of April 2010, Whiting (2010: 28) describes from the field, how the logistical aid operation is now fully underway, with access by air, available at Port-au-Prince once again, and Santo Domingo and Barahona in the Dominican Republic; access by sea available at Barahona and a secure network of spine roads available between the Dominican Republic and Haiti with transit hub points along the route for effective surface transportation.

Adams (2010: 1067), has investigated the state of sanitation in Haiti in the aftermath of the quake, concluding that it is in a particularly poor state. However, it is noted that the problem has been exacerbated by the poor waste infrastructure prior to the earthquake. As of April 2010, Adams believes that the shortage of solid waste drainage and latrines is one of the relief efforts 'most glaring gaps'. It is also noted that the forcing together of large populations of people in shelter camps, together with very poor sanitation and an imminent rainy season will dramatically increase risk of disease. However, the Active Learning Network for Accountability and Performance in Humanitarian Action (ALNAP) report (2008), expresses how it is important not to overstate the risk of disease as this will lead to a misallocation of resources. Only 3 out of 600 geophysical disasters led to disease epidemics, according to research published in the Emerging Infectious Disease Journal (2008). Basic medical care is currently being provided on a priority basis by various charities and military organisations.

Pauline Nee of John McAslan and Partners, reported at the SECED evening meeting in April 2010, entitled 'The Destruction and Rebuilding of Haiti', how their work to restore local markets has brought about a minor economic stimulation, particularly in the traditional artisan trades. Unfortunately however, this is a minor development in what has become a catastrophic humanitarian situation. As of May 2010, Heraty (2010: 36) reports that there remains approximately one million people with no access to shelter of any type. In general, particularly in inner city areas, the majority of collapsed buildings were constructed from steel and concrete, which offer no options of material recycling for temporary shelter construction by families who have lost their homes. However, despite the level of desperation, Da Silva (2007: 25) has identified the importance of deploying suitably skilled and experienced people with adequate solutions to disaster affected regions. The paper discusses how the ever increasing scale of disasters throughout the world has lead to agencies with no prior knowledge of the shelter sector to move into the field. Da Silva notes how providing shelter is a great deal more complex and has many more facets than it may appear; and how the creation of unsuitable solutions can result in precious funds being wasted, and in some cases, the affected population being put at greater risk.

The identification of the desperate situation which remains in Haiti, provides further justification for the pursuit of the investigation to determine whether the Hexayurt will provide a suitable solution.

# CHAPTER 4 - ELEMENTS OF DISASTER RELIEF SHELTERS

## 4.1 OVERVIEW:

Shelter is one of the most basic of human needs, utilised in its most primitive forms by even the earliest generations of the human race with the basic brief to provide protection from the elements and danger to life. Today, shelter forms a much more complex part of our lives, providing the basis for communities and environments for collections of people to fulfil safe and productive lives. The Universal Declaration of Human Rights (1948) recognises the significance of shelter in Article 25(1), listing durable housing as a right to which all humans are entitled. Taylor (1997) describes how indigenous architecture has, throughout time, been shaped by three primary factors:

- Environmental Impacts: Climate, Geography and Wildlife, including pests and predators
- Available Resources: Building materials, as well as energy and skilled labour;
- Human Needs: The space and cultural requirements for specific uses.

Whilst the developed world may take access to shelter for granted, many regions in the developing world operate in substandard and often dangerous shelter structures; as previously identified in Haiti prior to the earthquake of January 2010. Gupta (2010), in research carried out on world poverty, has identified the six most common causes of death in the developing world; too hot/too cold, hunger/thirst and injury/illness, arising from a variety of factors. Provision of shelter has a marked impact on at least four of the six, concluding that access to good shelter has a direct impact on rates of mortality.

Shelter fulfils a vast array of uses in the modern day world, but it could be argued that the most important of all, are those which provide a space we consider as home. The Organisation for Economic Co-operation and Development (OECD) (2004: 64), describe how housing is usually the largest category of property loss in a disaster situation, and how important the timely replenishment of housing is, in starting the recovery process in the aftermath of a disaster. In addition, Lizzaralde et al (2010: 77), Da Silva (2007: 26) and

The Sphere Project (2004: 208-211), reinforce the idea by discussing how the immediate deployment of an adequate shelter solution will reduce deaths, and prevent internal displacement and disorder, keeping a sense of some form of community:

> Shelter is a critical determinant for survival in the initial stages of a disaster. Beyond survival, shelter is necessary to provide security and personal safety, protection from the climate and enhanced resistance to ill health and disease. It is also important for human dignity and to sustain family and community life as far as possible in difficult circumstances. The Sphere Project (2004: 208)

However, whilst the need for a rapid deployment may point towards the production of a standardised prefabricated solution, there is a delicate balance in achieving acceptance of a shelter with respect to local cultural needs and expectations. As identified in section 3.3, a solution which is not suitable to meet the needs of an affected population could be a waste of time and money, and potentially make the situation worse. The complexities of achieving the right solution are discussed by The Sphere Project (2004: 208-209), where it is described that the type of response required to meet the needs of people and households affected by a disaster is determined by several key factors; including the nature and scale of the disaster and the resulting loss of shelter, the climatic conditions and the local environment, the political and security situation, the context (rural or urban) and the ability of the community to cope. Consideration must also be given to the rights and needs of those who are secondarily affected by the disaster, such as any host community. However, Lizarralde et al (2010: 26) recognises how it may be considered naive that there will be the time, skills or resources to provide an in depth analysis of all these factors in a disaster environment when time is so crucial. It is however the widely accepted that, in order to create a sense of ownership and community, the affected population must be included and consulted in any shelter project as much is as reasonably possible.

## 4.2 CURRENT SHELTER SOLUTIONS:

Quarantelli, E.L (1995: 43-53) has identified how, after a disaster, housing recovery occurs in distinct stages, which are highlighted in fig 4.2.1 below. Since disaster situations can vary widely in terms of type, severity, population, topography and climate, the stages may overlap and not all affected families will necessarily pass through each stage.

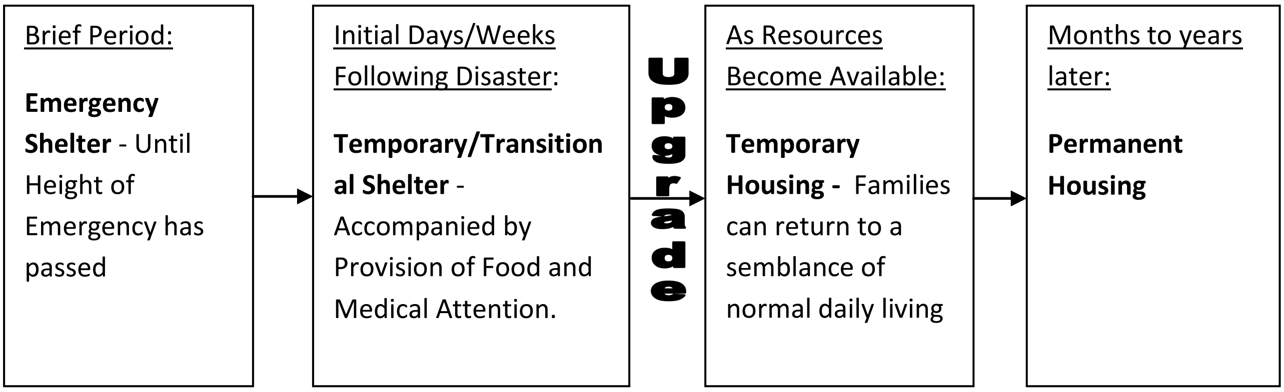


**Fig 4.2.1:** Stages of housing recovery (Quarantelli, 1995)

Each category, provides several options for shelter, however as previously identified it is not possible to apply the same solutions to every disaster throughout the world; each must be assessed individually and the most appropriate solutions available should be used.

Emergency Shelter:

Public Facilities: In developing countries, public buildings are often built to a higher standard than private dwellings and other buildings; and hence are more likely to survive during a disaster situation. Dependant on damage levels, public buildings can usually be retrofitted reasonably quickly to provide shelter for large groups. However, crowded conditions and lack of privacy make this solution suitable for a short amount of time.

Host Families: In the wake of a disaster, host families in less affected areas may be used to provide shelter. Host families are usually known to their lodgers, but this is not always the case. In the interests of minimising long term displacement from an affected area and hence slowing the recovery process, this should usually only be considered as a short term solution.

Tents: Tents are the preferred short term solution of aid agencies and military organisations due to their low weight and transportability. They are quick to erect and comparatively low in cost. However caution should be exercised in deploying such solutions. Da Silva (2007: 26) has noted incidence of the distribution of inadequate specification tents by well meaning aid organisations, particularly in response to the Pakistan earthquake in 2005. The tents did not provide the correct level of thermal insulation for the freezing conditions of mountainous regions, resulting in an increased problem for affected parties and a misallocation of vital funds.

Self Built Shelter: In the absence of a suitable deployed solution, families will inevitably begin to build temporary shelters, usually recycling materials from collapsed, damaged or empty buildings. This practise usually takes place in the absence of specialist guidance and should be avoided if possible as dangerous structures can result. Even the more robust of self built shelters are usually only appropriate for short periods of time.

<u>Temporary/Transitional Shelter:</u>

Rented Apartments: If, following a disaster, there remains a stock of undamaged apartments, governments may lease them to affected families; usually at subsidised rates. This is of course an ideal solution to provide shelter to those in need, however it is rarely the case, particularly in the aftermath of an earthquake. In the event that suitable apartment stock is available, numbers will be limited.

Shipping Containers or Mobile Homes: Shipping containers/mobile homes can provide a fully fitted prefabricated solution offering a good standard of medium term shelter. However, assuming such units are not already stored in the countries prone to disaster, good transport links are required to enable high volumes of containers to be transported. These rarely exist in disaster situations, and hence are seldom economical.

Modular Solution: Modular solutions are designed and tested for use in disaster prone environments. They consist of standardised 'flat pack' style kits that can be quickly and easily constructed by semi skilled labour and replicated on a mass scale. Some researchers, such as those involved with the Sphere Project (2004: 221) believes it is vital to involve the local population in the design of relief shelters as much as possible; and simply introducing standardised systems into disaster affected communities rarely offers an adequate solution.

Modular solutions, particularly if required on a mass scale, tend to bring problems of specialist material supply and distribution.

In general modular solutions for discrete dwellings are under exposed, in fact only large communal modular dwellings, hospitals or feeding centres currently exist in the general domain.

Temporary Housing:

Temporary housing is generally constructed once an adequate supply of skilled labour and building materials can be delivered to the affected area. There are many types of rudimentary building types or specialist modular solutions that have been developed for this purpose.

**Sources:** Lizarralde et al (2010:71-73), Davis and Lambert (2002: 547-585), OECD (2004: 63-71), Da Silva (2007: 25-28)

Shelters can be clustered in mass housing camps, which carries a multitude of risks, particularly to vulnerable groups; or units can be individually dispersed on or near the property of the affected family. Where possible Lizarralde et al (2010: 73) describe how it is preferable that temporary houses be located on or near to a family's existing property, as this avoids further disruption for family members and allows them to use existing services; as well as maintaining social networks. However, this is not always possible. In high-density urban areas were families are living in apartments, there may not be enough available land nearby. Or if the entire infrastructure is wiped out in an area, it may be some time before water and electricity can be restored, so clustering becomes necessary, regardless of the risks and disadvantages.

The Hexayurt is designed as a form of modular transitional, single dwelling shelter. With the benefits according to Gupta (2010: 3), that it offers a very constructible unit of widely available standard engineered timber boards, CLS (Canadian Lumber Standard) sections, wood glue and steel strapping. The hexagonal form also contributes to increasing security in mass camp scenarios, offering the option of connecting the units together in a larger hexagon shape to form a central courtyard area for washing, cooking and cleaning; thus encouraging a sense of community and dramatically increasing security. This form of construction is recognised as a security and utility benefit by Taylor (1997: 64), see fig 4.2.2.

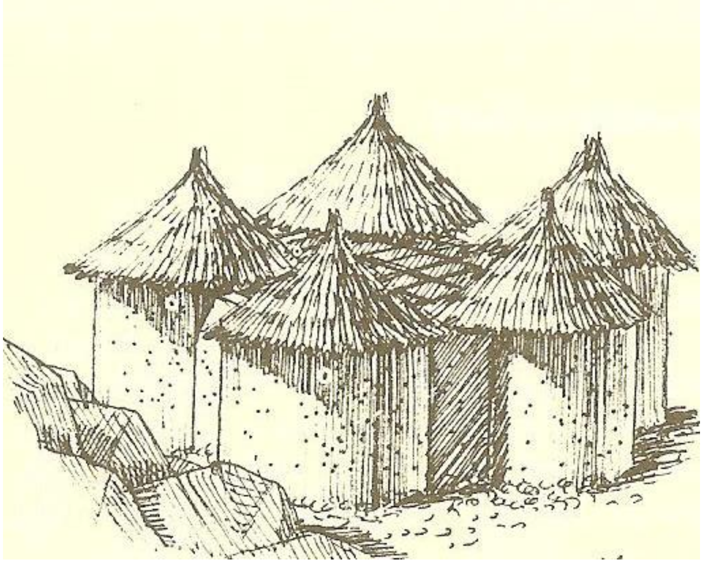

**Fig 4.2.2:** Mesakin Quisar Cluster Dwelling, Sudan

Taylor (1997: 64)

**4.3 STANDARDS:**

Da Silva (2007: 27) discusses how global shelter standards are a way of effectively overcoming the shortfall, identified in chapter 3, of skills in an ever more demanding sector resulting from the increasing scale of world natural disasters. The paper also notes how other humanitarian aid sectors such as water and sanitation, and food and health, are covered by numerous guidance and tools and complimented by various courses and degree programmes; concluding that the shelter sector suffers from a distinct lack of guidance.

Crook (2006: 14) has identified the 12 qualities which contribute to habitability in transitional shelters, and how they match against standard shelter objectives.

*Table 1: Habitability qualities and transitional shelter objectives*

| Habitability qualities | Transitional shelter objectives | | | | | |
|---|---|---|---|---|---|---|
| | Environmental protection | Comfort | Dignity | Household | Health | Safety |
| Weatherproof | * | * | | | | |
| Temperature | * | * | | | | |
| Ventilation | | * | | | | |
| Light | | * | | | | |
| Privacy | | | * | | | |
| Space | | | * | * | | |
| Cooking | | | | * | * | |
| Water and sanitation | | | | * | * | |
| Vector control | | | | | * | * |
| Safety (fire, toxicity) | | | | | | * |
| Security | | | | | | * |
| Structurally sound | * | | | | | * |

**Fig 4.3.1:** Table Showing Habitability Qualities Against Transitional Shelter Objectives

The table offers a checklist with which to assess a proposed shelter. Whilst the need to prove the structural stability of the Hexayurt in the Haitian environment has already been identified, the table also highlights the many other key technical factors against which it should be assessed prior to deployment.

Crook proceeds to assess the habitability qualities against the various shelter components in a similar format to that of fig 4.3.1., providing guidance toward the elements that should be assessed to approve a shelters structural stability.

| Table 2: Habitability qualities and shelter components | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Habitability qualities | Shelter components | | | | | | | | | | | |
| | Form (area, height) | Foundation | Frame | Roof | Walls | Gables | Windows | Doors | Partitions | Extensions | Site (layout/Location) | Floor |
| Structurally sound | * | * | * | * | * | | | | | | * | |
| Weatherproof | * | | | * | * | * | | | | | | * |
| Temperature | * | | | * | * | * | * | | | | | |
| Ventilation | * | | | | | * | * | * | | | | |
| Light | * | | | | | | * | * | | | * | |
| Privacy | * | | | | | | * | * | * | | | |
| Vector control | | | | | * | * | * | * | | | | * |
| Safety (fire, toxicity) | | | * | * | * | * | | | | | * | |
| Security | | | | | * | | * | * | | | | |
| Cooking | * | | | | | * | * | | | * | | * |
| Water and sanitation | | | | * | | | | | | | * | |
| Space | * | | | | | | | | | | * | |

**Fig 4.3.2:** Table Showing Habitability Qualities Against Transitional Shelter Components

With regards to humanitarian shelter projects, The Sphere Project - Humanitarian Charter and Minimum Standards in Disaster Response (2004), are widely regarded as the most important document to refer to. The project is an initiative launched in 1997 by a group of humanitarian NGO's and the Red Cross and Red Crescent movement to create a humanitarian charter to identify minimum standards to be attained in each of the five key sectors (water supply and sanitation, nutrition, food aid, shelter and health services). The specific shelter section includes standards on strategic planning, physical planning, covered living space design, construction and environmental impact. It is beyond the scope of this project to assess the hexayurt against all of these facets, however those with respect to construction are relevant and have been assessed accordingly below. For clarity, the standards have been included. Further evaluation of the suitability of the Hexayurt has been made in chapter 5.

**The Sphere Project (2004: 224-229) Shelter Construction Standards:**

1. Sourcing of shelter materials and labour

Standard:

Livelihood support should be promoted through the local procurement of building materials, specialist building skills and manual labour. Multiple sources, alternative materials and production processes, or the provision of regionally or internationally sourced materials or proprietary shelter systems are required if the local harvesting and supply of materials is likely to have a significant adverse impact on the local economy or the environment. The re-use of materials salvaged from damaged buildings should be promoted where feasible, either as primary construction materials (bricks or stone masonry, roof timber, roof tiles, etc.) or as secondary material (rubble for foundations or levelling roads, etc.). Ownership of or the rights to such material should be identified and agreed (see Shelter and settlement standard 6, guidance note 3 on page 228).

Assessment against the hexayurt:

It is conceivable that neighbouring developing economies could be stimulated by purchasing materials from them in the event of no supply already in Haiti. US military may also be in a position to supply materials. It is unlikely that material from collapsed buildings will be salvageable for use with the Hexayurt.

2. Participation of affected households:

Standard:

skills training programmes and apprenticeship schemes can maximise opportunities for participation during construction, particularly for individuals lacking the required building skills or experience. Complementary contributions from those less able to undertake physically or technically demanding tasks can include site monitoring and inventory control, the provision of child care or temporary accommodation and catering for those engaged in construction works, and administrative support. Consideration should be given to the other demands on the time and labour resources of the affected population. The inclusion of food-for-work initiatives can provide the necessary food security to enable affected households to actively participate. Single women, female-headed households and women with disabilities are particularly at risk from sexual exploitation in seeking assistance for the construction of their shelter. The provision of assistance from volunteer community labour teams or contracted labour could complement any beneficiary contributions (see Participation standard on page 28).

Assessment against the hexayurt:

By being so readily constructible (see chapter 5), the ability of the Hexayurt to engage the local community is one of its greatest assets. The minimal skills required to build a Hexayurt can be passed on, along with standard instructions to adjoining villages and towns, resulting in many families becoming safely housed in a comparatively short space of time.

3. Construction standards:

Standard:

Standards of good practice should be agreed with the relevant authorities to ensure that key safety and performance requirements are met. In locations where applicable local or national building codes have not been customarily adhered to or enforced, incremental compliance should be agreed.

Assessment against the hexayurt:

Set of standards for the construction of the Hexayurt to follow research.

4. Disaster prevention and mitigation:

Standard:

The design should be consistent with known climatic conditions, be capable of withstanding appropriate wind-loading, and accommodate snow-loading in cold climates. Earthquake resistance and ground bearing conditions should be assessed. Recommended or actual changes to building standards or common building practices as a result of the disaster should be applied in consultation with local authorities and the disaster-affected population.

Assessment against the hexayurt:
This forms the main objectives of this research project, the results of which will provide a conclusion as to whether it is structurally suitable for the Haitian environment.

5. Upgrading and maintenance:

Standard:
As emergency shelter responses typically provide only a minimum level of enclosed space and material assistance, affected families will need to seek alternative means of increasing the extent or quality of the enclosed space provided. The form of construction and the materials used should enable individual households to incrementally adapt or upgrade the shelter or aspects of the design to meet their longer-term needs and to undertake repairs using locally available tools and materials.

Assessment against the hexayurt:
The Hexayurt offers an immediately constructible, waterproof shelter solution to move affected families into quickly, offering a dwelling more robust than an emergency tent. Certain further upgrades to meet individual needs may be added as material availability and money will allow. The most likely upgrades should be tested/designed for in subsequent research, and guidelines should be issued to ensure structural stability is not compromised.

6. Procurement and construction management:

Standard:

A responsive, efficient and accountable supply chain and construction management system for materials, labour and site supervision should be established that includes sourcing, procurement, transportation, handling and administration, from point of origin to the respective site as required.

Assessment against the hexayurt:

This is facilitated by the choice of widely available materials and constructability of the Hexayurt.

## 4.4 COST

Lizarralde (2010: 79) has identified how one of the biggest problems with transitional shelter/temporary housing programmes, is how expensive they *can* be in relation to their lifespan. The cost for building the unit and infrastructure, the maintenance and de-installation can in certain circumstances amount to as much per square meter as permanent solutions. Davis (1978: 112) also remains sceptical, claiming that re-building twice is not feasible from a cost or a time perspective.

However other sources, such as Geipel (1991: 89) and the United Nations Disaster Relief Organisation (UNDRO) (1982: 154) agree on the importance of transitional shelter programmes, and how providing durable housing, previously identified in chapter 1 as a human right, is key to holding communities together in times of extreme adversity, in fact repaying in dividends by adding to the overall speed of recovery.

In a disaster on the scale of the Haiti earthquake, the bulk of money for shelter programmes is almost certainly to be provided from aid donations from governments, charity organisations and NGO's. With such funds being limited, it is vital for the cost of units to remain as low as possible. To offer a comparison with the Hexayurt against similar units, Lizarralde (2010:80) notes how, in the aftermath of the Turkey earthquakes in 1999, the NGO one room timber shelters cost approximately $1000 each. Gupta (2010: 15) estimates the finished cost of a Hexayurt in Haiti cost at between $200 and $500 per unit. Whilst the two may not be directly comparative, this demonstrates roughly how cost effective the Hexayurt as a solution could be.

# CHAPTER 5 - THE HEXAYURT

## 5.1 INTRODUCTION

The aims of this chapter are twofold; to fill in the gaps which exist in the research so far and to bring together the various elements from the project thus far, in order to develop a rationale for progression towards proving the suitability for the Hexayurt for use in the Haitian environment.

## 5.2 THE HEXAYURT

### 5.2.1 Introduction

The Hexayurt itself is in effect a modern day constructible, analysable adaptation of a traditional form of 'yurt' building. The yurt has existed as early as the 17th Century and originated from the nomads of Central Asia. Like the Hexayurt, a traditional yurt is designed so that it can be dismantled into pieces and transported, usually on camel back. It consists of a circular plan, outer lattice of timbers bound with rope which form the walls, supporting a number of roof poles held together at the 'crown', which acts as a compression ring (see fig 5.2.1.1). The walls are insulated with felt type blankets and overlain with a waterproof canvas. Loads are resisted because the tightly bound ropes and lattice structure walls induce monolithic behaviour, which is explained in more depth in section 5.2.2.

The basis of this research project is to analyse the structure of the hexayurt, and its capability to operate in the Haitian environment. However, as identified by Crook (2006: 14) in chapter 4, there are many facets to consider to prove the overall adequacy of a shelter for a particular environment. It is recommended that these are investigated, in line with The Sphere Project guidelines.

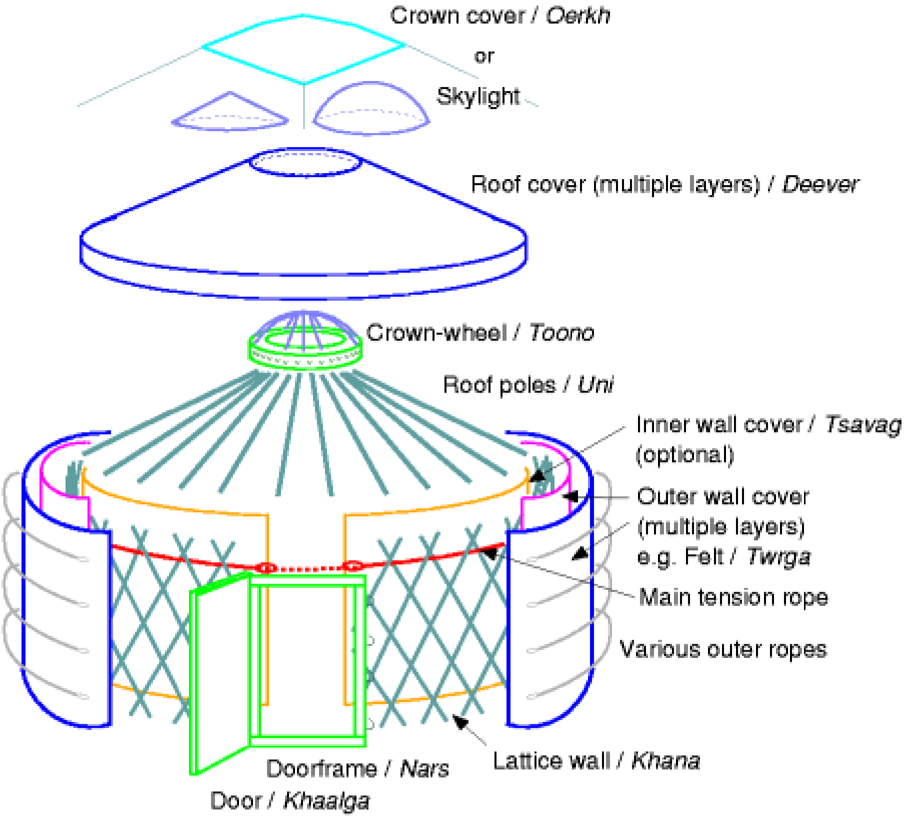


**Fig 5.2.1.1:** The Construction of a Traditional Yurt; by SimplyDifferently.org

**Fig 5.2.1.2:** A Completed Traditional Yurt in Mongolia; by Wikipedia.org

5.2.2 Structural Layout and Construction

The following section describes the structural layout and construction method as developed by Vinay Gupta in the paper 'The Hexayurt in Haiti?' (2010). To date, the method has undergone no engineering analysis and has been designed on principles of constructability and rule of thumb only.

Walls:

The walls of the Hexayurt are constructed from 6 No standard sized sheets (1.2m x 2.4m) of engineered timber board, laid on the long edge and joined at a 120˚ internal angle. A 6" cut is made on the edge of each board, to allow the roof to overhang, aiding drainage during the rainy season.

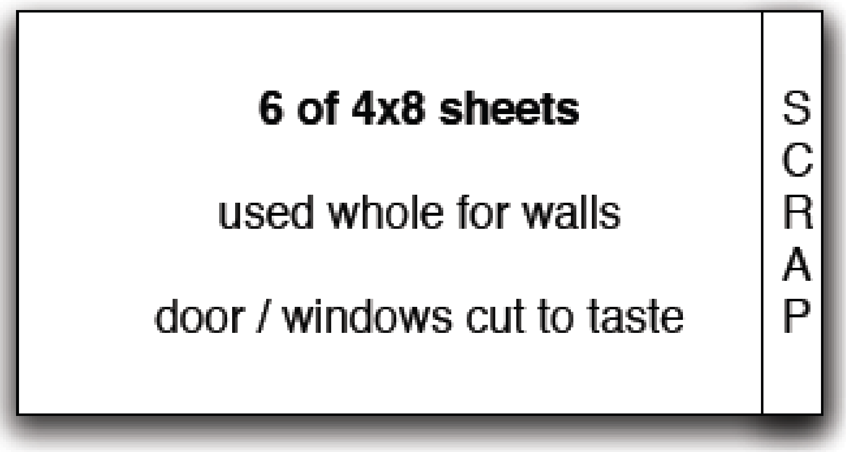


**Fig 5.2.2.1:** Hexayurt Wall Board (Gupta (2010: 8))

The wall joints consist of 120˚ blocks cut from 2 x 4" CLS (Canadian Lumber Standard) timber which are screwed through. The Joint is reinforced with exterior grade foaming wood glue and mild steel straps.

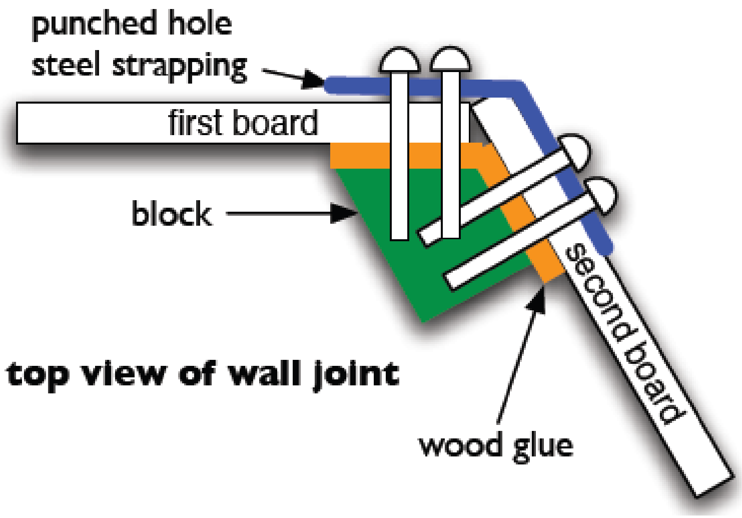


**Fig 5.2.2.2:** Top View of Wall Joint (Gupta (2010: 13))

Roof:

The roof sections are formed from 6 No standard sized sheets (1.2m x 2.4m) of engineered timber board cut corner to corner. The diagonally cut peices are joined back to back to form a triangular panel; using exterior grade foaming wood glue, screws and small timber blocks cut from 4 x 2" CLS.

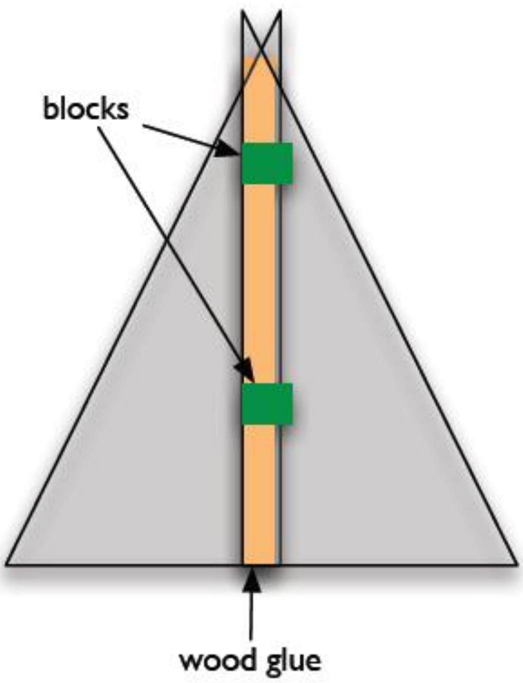


**Fig 5.2.2.2:** Top View of Roof Panel and Joint (Gupta (2010: 9))

The preformed roof sections are joined together using 150˚ blocks cut from 2 x 4" CLS (Canadian Lumber Standard) timber, which are screwed through. The Joint is again reinforced with exterior grade foaming wood glue and mild steel straps.

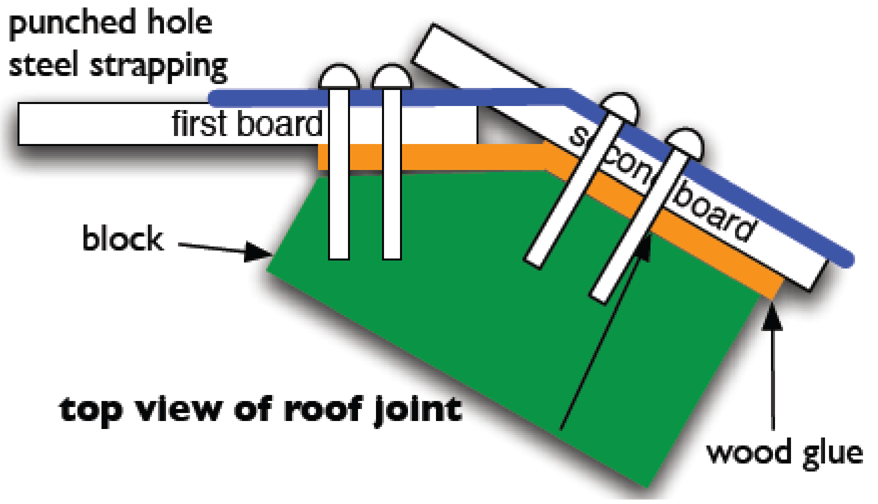


**Fig 5.2.2.3:** Top View of Roof Joint (Gupta (2010:13))

The roof section is constructed on the ground as a separate entity to the walls using a temporary central support prop. The roof is subsequently lifted into position on the walls and screwed to the eaves block joints, which are made from 120˚ 4 x 2" CLS, and glued along the seam.

<u>Ground Anchorage:</u>

The Hexayurt is anchored to the ground using bent steel reinforcement bar hammered into the ground and passed through holes drilled into the wall panels.

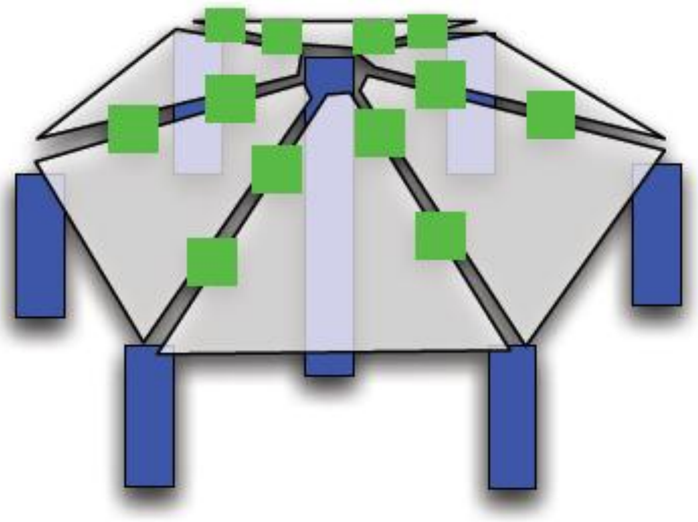

**Fig 5.2.2.4:** Approximate Layout of Roof Joints (Gupta (2010: 12))

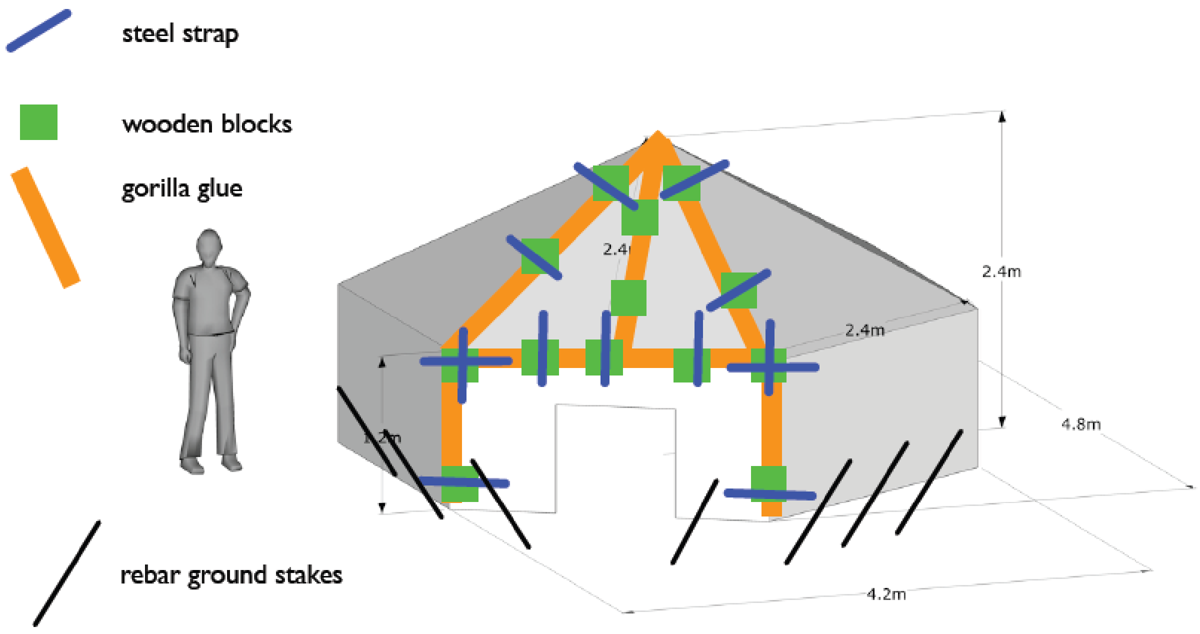


**Fig: 5.2.2.5**: Isometric View Showing Approximate Structural Layout of Hexayurt (Gupta (2010: 2))

5.2.3 Structural Overview

The form of the Hexayurt was developed for two primary reasons; constructability and space. The hexagon allows standard sized engineered boards with 6" removed, to be used for the walls and corner to corner cuts to be used to create a roof of reasonable pitch (30˚), so as to allow head room and easy construction (Gupta 2010). Increasing the number of walls to create a heptagon or octagon, would increase the amount of work required to complete construction for only a very small increase in floor space, whilst decreasing the pitch of the roof so as to reduce headroom dramatically. Decreasing the number of walls to a pentagon or square plan would reduce floor space, whilst creating an unrealistically large roof pitch.

However, the form also contributes to the Hexayurts structural stability. Primarily, when the joints of the structure are glued it is expected to behave monolithically, similar to the aforementioned traditional yurt, as a 'stressed skin' or 'monocoque'. This means that both vertical and lateral loads are resisted by the distribution of stresses through the tensile capability of the various joined boards. Typically, stressed skins act in tension only and hold very little ability to resist direct compression. The layout of walls in a hexagonal shape, provides bracing walls to resist lateral loads from any direction. The timber block joints act to secure the structure in place prior to gluing; and together with the steel strapping increase stiffness at joint locations. An exact distribution of stresses could be obtained by creating a finite element model, which is beyond the scope of this project. Figure 5.2.2.5 shows the structural layout of the hexayurt.

In addition, the hexagonal form of the Hexayurt provides a less turbulent path for the wind to pass around it, in comparison with a form more flat fronted. This will minimise the loads induced on the boards and joints.

5.2.4 Materials:

Since the Hexayurt has been designed around principles of constructability and material availability, the materials which may be used in the analysis and testing phase are somewhat predetermined; and it is beyond the scope of this project to pursue in identifying additional materials which may also be suitable outside of this remit. It is however necessary that an understanding of the materials identified by Gupta (2010) is developed, in order that an accurate structural analysis is made. Where appropriate, comparisons have been made between materials.

Specific strength properties of materials have been listed in the detailed analysis and joint design sections in appendix 2 and 3 respectively.

Hexayurt Materials:

1) Engineered Board:

It is proposed that the walls and roof of the Hexayurt are made from engineered timber board. The parameters of cost, availability and exposure, as identified by Gupta (2010), allow for only 2 realistic options; Plywood and OSB (orientated strand board). The IStructE/TRADA manual (2007: 27) Table 3.56, lists both ply and OSB as standard materials suitable for use in timber structures.

<u>Plywood:</u>

Plywood is a preformed engineered timber panel, which is made up from thinner sheets of timber compressed and glued together with the grain direction of each layer (or ply) at right angles to each other. Taylor (2002: 540) notes how an odd number of plies are used in the production of ply wood, resulting in a symmetrical formation of grain directions about the central sheet. This property enhances the structural performance of the material when exposed to moisture, as the expanse of internal plies will result in equal and opposite bending effects, keeping distortion to a minimum. As a result, plywood can be used in situations of varying moisture contents.

Porteous and Kermani (2007: 21) describe how plywoods behave more isotropically in the plane of the sheet than solid timber, owing to the absence of internal knots and splitting. This results in a much higher flexural strength than solid timber when loaded across the grain. When loaded parallel to the grain however, plywood has a lower flexural strength than solid timber.

Porteous and Kermani (2007: 21) note how the use of water and boil proof resins (WBP) and hardwood timber grades in the manufacture of certain grades of plywood, allow them to be used in exterior situations and are suitable for service class 3. The WBP resins also give added protection against fire in comparison with ordinary timber.

Taylor (2002: 540), explains how the working properties of plywood are similar to those of ordinary timber, although it may be nailed or screwed without risk of splitting since there are no cleavage planes (orientated strand like fibres which make up ordinary cut timber). This is reflected in its most common uses, which is structural purposes as well as shuttering for concrete formwork. Plywood is also commonly used for cladding and other decorative exterior purposes.

The IStructE/TRADA manual (2007: 27) notes how exterior grades of plywood may be preferable to OSB for more humid environments or situations where wetting may occur or under long term loading (i.e. in flat roofs).

The vast range of plywood types and grades can make design challenging in the event that the grade to be used is not apparent.

<u>Orientated Strand Board (OSB):</u>

OSB consists of strands of wood, approximately 75mm in length and 0.5mm thick, compressed and bonded together by synthetic resins in layers. Porteous and Kermani (2007: 25) Outer layers consist of strands orientated in the long direction of the panel, with inner layers arranged at random. This cross orientation results in a board structure which behaves similar to plywood, at a much lower cost. As with plywood, Taylor (2002: 541) notes how OSB has a major and a minor axis which should be apparent by inspection. For optimum performance, the major axis should be aligned with the stress.

As in the case of plywood, exterior grade OSB (No 3, load-bearing and No 4, heavy duty) is bonded using water and boil proof resins (WBP).

The IStructE/TRADA manual (2007: 27) describes OSB as the preferred choice on cost grounds for timber frame wall panels and the webs of I-joists. Also used for floor decking, particularly the structural decking in party floors. High creep under long term Loading.

The fire resistance

Conclusion:

This analysis of the engineered boards selected by Gupta shows at pre design/testing phase for both OSB and Plywood to be suitable boards for use with the hexayurt

How the strength of the board itself is critical to the stability of the unit, is subject to further testing and design later in the project.

2) Timber

Plain timber sections are required to form the block joints of the Hexayurt unit.

Cobb (2008: 117) describes how commercially available timber is defined as hardwoods and softwoods according to their botanical classification rather than their physical strength. Hardwoods being from broad leaved, deciduous trees. Softwoods are from conifers which are typically evergreen with needle shaped leaves, and in general, grown considerably more rapidly than hardwoods.

Within this grading, timber is specified by a strength class which combines the timber species and strength grade. Strength grading, which is carried out visually or by a machine, is the measurement or estimation of the strength of individual timbers, to allow each piece to be used to its maximum efficiency.

Eurocode 5 and BS5268 for timber design both list strength softwood classes from C14-C40 (C being for coniferous) and hardwood classes from D30 - D70 (D being for deciduous). The number refers to the ultimate bending strength in N/mm$^2$ before application of safety factors required for British design. Lower classification, weaker timber is grown more rapidly than higher classification, stronger timber, which can be identified visually by inspecting the varying distance between annual growth rings. The greater the distance which exists between growth rings, the less dense the timber is, and hence the weaker it is.

Owing to its speed of growth, the most commonly available timber is the softwood, C classification timber at the lower grades of 16 and 24.

The most commonly available sawn timber type for structural purposes in the USA and UK is CLS (Canadian Lumber Standard). CLS timber is generally used for structural and other construction purposed that remain hidden; such as stud partitioning. CLS describes the region of origin (Canada or Europe) and is available for the previously identified standard strength classes. CLS is available in standard section sizes and lengths, and can usually be identified by the bevelled edge left from the cutting machine.

The previously discussed likelihood of high moisture will have a marked impact of the overall strength of the CLS timber when used as a block joint. Taylor (2002: 503), displays how timber of high moisture contents will be subject to decay, shortening life span and lowering strength. He continues to describe how, at common moisture contents, in the region of 15%, the strength will be approximately 40% higher than at saturated rate as experienced by service class 3. Taylor (2010: 526). As a result of the probable high moisture content however, timber shrinkage, which occurs at moisture contents much lower than service class 3 is unlikely to be a matter for concern.

3) Steel Strapping

The steel strapping at the joints of the Hexayurt, as defined by Gupta (2010: 2), will be dependent on the further development of the design process. Since steel is available in a vast array of sizes and grades, and Gupta has not provided guidance as to which of these may be required; it is not appropriate at this stage to carry out an in-depth analysis.

Steel strapping is commonly available for use in construction application in a variety of sizes and grades, often with high tensile capacities. In the interests of constructability, it would be appropriate that a pre-drilled solution be specified.

4) Glue

There are a vast array of wood adhesive products available on the market. Gupta suggests the need for a brand named 'gorilla glue', which is a polyurethane adhesive. Such adhesive provides medium strength when bonding to flat timber surfaces and expands during the curing process to fill voids. However the glue is a harmful substance, and the risk of exposing unskilled users in the field must be assessed.

Strengths in bonding specific materials in specific conditions can only be attained by testing to a code, such as BS EN 302-7: 2004 - Adhesives for Load Bearing Structures - Testing Methods.

A major drawback in the development of strength in an adhesive, will be the likely presence of dust and high humidity in the Haitian environment.

5) Screws

Wood screws are used in place of nails in applications requiring higher capacities, in particular in situations where a greater withdrawal capacity is required. They can be used for timber-timber joints, but are particularly effective for steel-timber and board-timber joints. Screws should be fixed by being threaded into timber, not by being hammered into position and the characteristics strengths given for screws are based on this assumption. where screws are used in softwood connections

Specific requirements with regards to screw grades are discussed in further detail in subsequent sections.

The Most commonly available types are countersunk head, round head or coach screws.

5.2.5 Constructability

It has been identified from the research conducted in the early chapters of this project, that constructability is a parameter which underpins the success of the Hexayurt in the field. Not only from the perspective that untrained, semi-skilled people in the local population must find it possible to build; but also, and possibly more importantly from the perspective that if a solution is deployed that is not reasonably simple to build correctly, those in the affected population will not build it correctly and hence the structure will be compromised.

Whilst an in-depth investigation into constructability may be necessary for a subsequent project in order to streamline the process for mass production, it was deemed necessary to undertake two practical investigations into the constructability of the unit, in order to decipher whether this could have an impact on the subsequent detailed analysis and laboratory testing phase.

Two constructability tests were carried out in the form of a 1:10 scale card model (as a low cost initial exercise), and a full scale trial using 9mm thick OSB with the help of unskilled/untrained people at a recent festival hosted by the charity Practical Action.

**1) 1:10 Scale Model:**

The 1:10 scale model was constructed by replicating the wallboards using 1.5mm thick card, and replicating the joints with 4mm thick foam board and pins. The glue and metal straps were replicated by masking tape.

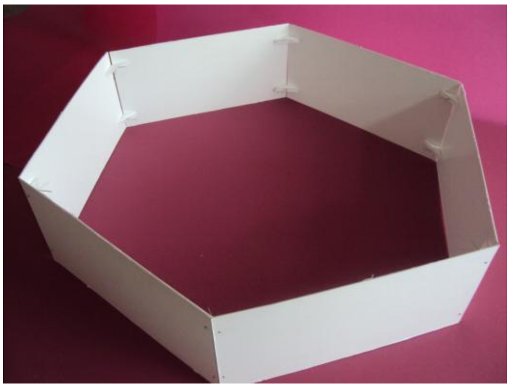

**Fig: 5.2.5.1:** 1:10 Scale Wall Joint Using Pins and 4mm Foam Board

**Fig: 5.2.5.2:** 1:10 Scale Wall Section Completed

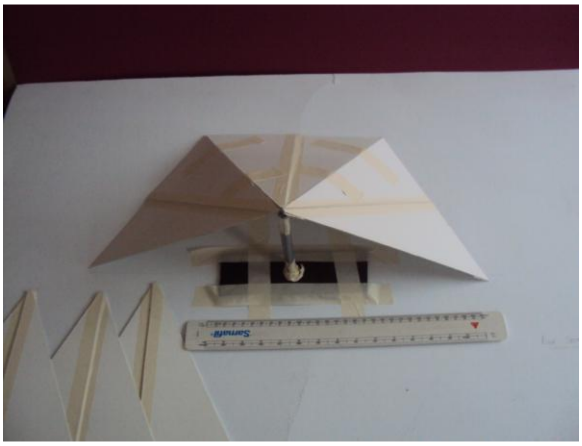

**Fig: 5.2.5.3:** 1:10 Scale Roof Under Construction

**Fig: 5.2.5.4:** 1:10 Scale Completed Hexayurt and Ergonome

**Fig 5.2.5.5:** 1:10 Scale Wall Section and Ergonome

**Photographs for Constructability Test 1; 1:10 Scale Card Model**

Observations:

i. The inclusion of the glue (replicated in the model as masking tape), increased the stability of the unit significantly. This is because the model no longer . However, as previously identified, it is not appropriate to make direct assumptions on the stability of the structure when different materials to those intended, are used.

ii. Wall section appeared quick and simple to construct, however roof was cumbersome and continued to collapse inwards from its central support post until the foam board joints were fitted.

iii. It is not known how many people will be required to lift the roof section into place on the wall section. It was anticipated that this will be a cumbersome operation, and matching joints for an adequate connection may be a problem.

**2) Full Scale Hexayurt:**

A full scale Hexayurt was constructed at the Practical Action charity festival, using 9mm OSB(3), 4 x 2" C16 CLS for Block Joints, and 10 x 3" Wood Screws. No Glue or steel straps were used.

**Fig: 5.2.5.6:** 120˚ Wall Block Joint

**Fig: 5.2.5.7:** Completed Wall Section

**Fig: 5.2.5.8:** Roof Under Construction

**Fig: 5.2.5.9:** External Eaves Joint

**Fig: 5.2.5.10:** Construction of Roof Panels

**Fig: 5.2.5.11:** Completed Full Scale Hexayurt

Observations:

i. Roof can be easily lifted into position with 12 people.

ii. 120 ˚ Wall Joints are simple to achieve good construction.

iii. 150˚ Much more difficult to form good connections, as much of the screwing work is done effectively 'blind'.

iv. 120˚ Eaves Joints are particularly unpredictable, as roof and walls constructed separately. It was only possible to drive 1 screw through some of the external eaves joints.

v. Unit felt very stable, even in the absence of glue and strapping.

## 5.3 RATIONALE FOR ANALYSIS, DESIGN AND TESING

The research in Chapter 5, has presented a clear rationale for the progression of the project into the analysis, design and testing phase.

Constructability and speed of deployment have been repeatedly highlighted as crucial factors in the success of the Hexayurt for both the Haiti disaster and in future disasters. Both factors can be linked directly to the materials used in the construction of the unit, in two different ways. Using the most basic, simple materials will facilitate constructability amongst groups of un-skilled people in disaster affected regions and ensure that the units are constructed as designed. Material availability is also of paramount importance, and the procurement of large volumes of specialist products, such as glues and straps, will risk the delay of a deployment. It may also be identified from the materials research that, under the environmental circumstances, it is unrealistic to rely on a glue type material for the majority of the stability, in attempting to make the unit act monolithically.

Since it has been observed from the full scale constructability test that the unit will stand using only block joints, without the need for glue and straps as suggested by Gupta (2010), the analysis, design and testing phase will progress on this basis, i.e.:

'Is it possible for the Hexayurt to be suitable in the Haitian environment when constructed from engineered timber board and timber and timber block joints only'

However, this alters the way in which the Hexayurt behaves as a structure, which has been considered as part of the analysis and design. From engineering judgement, it can be said that, in the absence of glue and straps, the unit behaves in part like a framed structure, as the boards act in bending between the joints, where high concentrations of stress develop. The triangular form of the roof behaves most similarly to a geodesic dome, requiring a tension ring at its base (along the top of the walls); and compression ring at the top. In order to analyse the design, a simplified approach has been taken, described in further detail in appendix B.

For the purposes of design, it has been assumed that the unit is fully fixed to the ground. Future analysis into the holding down capacities of the driven reinforcement bars in various ground conditions will be required.

## 6.1 WIND ANALYSIS

A detailed wind analysis in line with BS6399-2: 1997 has been carried out to determine the magnitude of the worst case wind loads acting on the structure and how and how they may be distributed.

For clarity, the calculations have been omitted from this section, and included in appendix A. The calculated loads have been applied to the subsequent sections for determination of applied design loads to the joints.

As an extra visual analysis, and to confirm that the assumptions made during the code based analysis, a smoke tunnel test was carried out using the 1:10 scale card model created for chapter 5; the most relevant photos from which are displayed below:

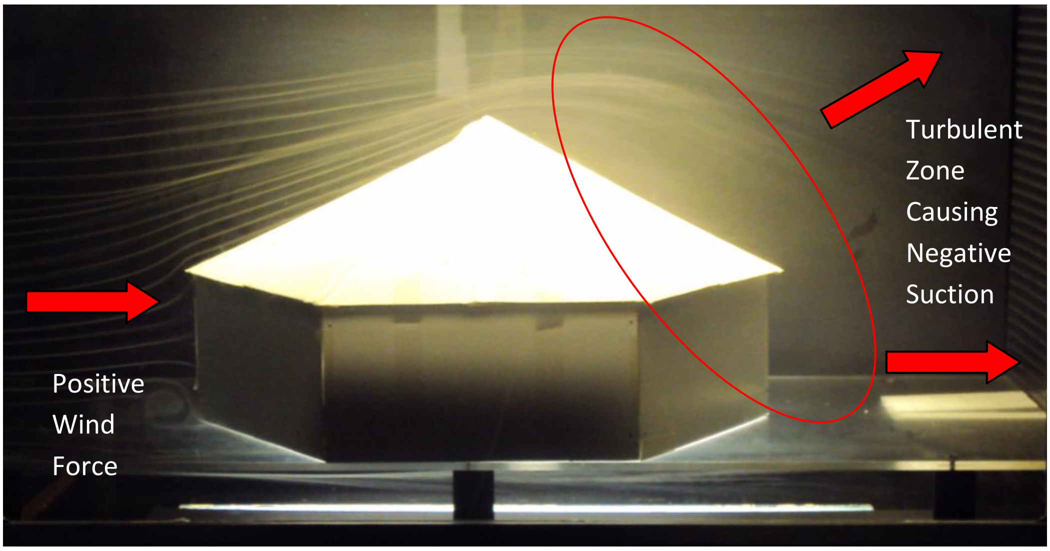


**Fig 6.1.1:** Hexayurt Elevation, Showing Applied Lateral Wind Streams and Turbulence Zones

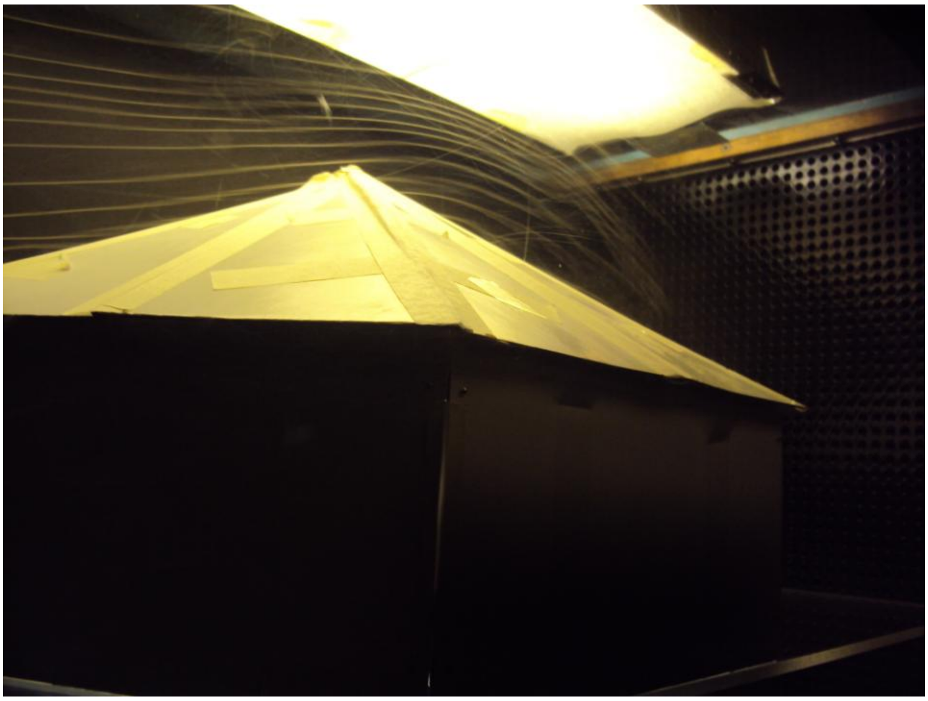

**Fig 6.1.1:** Wind Streams Over Peak of Roof

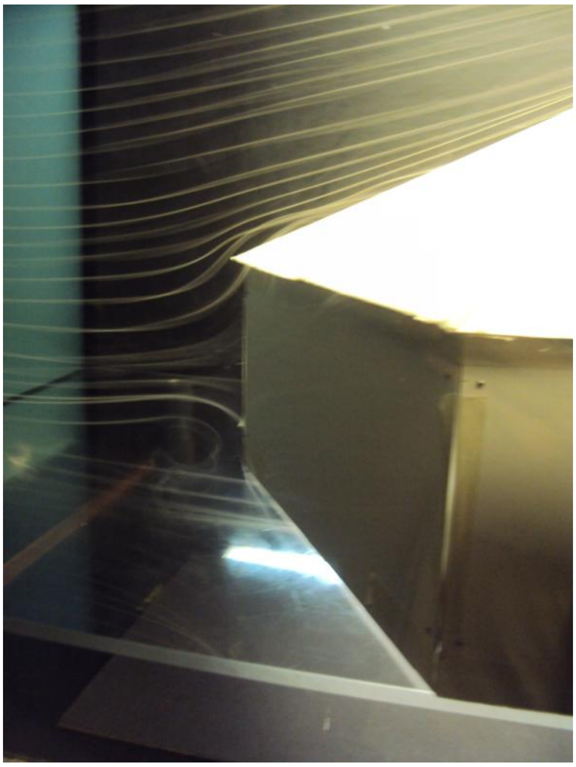

**Fig 6.1.1:** Wind Streams Showing Turbulent Lift at Overhang

In summary of the smoke tunnel test, the wind appears to move around the Hexayurt as per the wind code analysis, with the exception of the apparent uplift created at the eaves overhang. This was not initially noted in the wind analysis as the simplified model created for the analysis neglected the presence of an overhang. This modification will be applied to subsequent design calculations (see guidance note appendix B, sheet 15).

## 6.2 ANALYSIS

Following the determination of the various vertical and lateral loads acting, a static analysis of the Hexayurt has been carried out. This is critical in order to determine the magnitude and direction of the forces acting on the joints. Again, for clarity, the calculations have been removed from this section and included in appendix B at the rear of this report. A simplified model of the structure has been used in the analysis, which is discussed in detail on sheet 1 of appendix B. A summary of the results of the analysis is presented on sheet 13 of appendix B.

## 6.3 SEISMIC CONSIDERATIONS

As previously discussed, Haiti is in an earthquake hazard zone. Following the devastating activity of the Enriquillo-Plantain Garden fault in January 2010, there now exists a raised risk of a reoccurring earthquake during the design life of the Hexayurt. It is therefore necessary to consider its behaviour under seismic loading. Whilst a detailed seismic analysis is a complex topic beyond the scope of this project, it is appropriate to make initial observations as to the suitability of the Hexayurt for earthquake situations.

Daly (1972 :1) describes how the foundations and lower parts of a building move in tandem with the ground as it shakes due to seismic activity. However, inertia of the upper parts of the building causes a slight delay in this movement, leading to stresses building up; with cracking, potentially leading to complete failure, occurring at weak zones. For this reason taller, heavier buildings incur higher stresses and are hence more susceptible to damage. Smaller lightweight buildings, in particular with lightweight roofs are desirable in earthquake areas.

However, as can be viewed in the static analysis phase, the Hexayurt is a 'top heavy' structure, with the roof imposing a relatively large line load onto the top of the narrow wall boards. This increases the risk of inertia and high stresses building up, particularly at the eaves joint. Reaching a detailed conclusion will be a result of further investigations into the foundations.

Daly (1972: 4) continues to describe how a major factor in providing resistance to earthquakes, particularly in small structures, is to ensure all parts are adequately tied together monolithically. This allows stresses to be distributed around a structure and reduces the risk of discrete areas of failure.

In order to draw conclusions regarding the seismic suitability of the unit, observations have been be made in the subsequent sections, as to the capacity of the joints in tension, reflecting their ability to tie parts of the unit together; as well as the flexibility of joints prior to failure.

## 6.4 LABORATORY TESTING

### 6.4.1 Introduction

As prior to this project there had been no engineering analysis or testing of Gupta's hexayurt design, there remains a vast number of variables which could be investigated in order to prove its viability for the Haitian environment. Following initial research and review of existing literature, the timber block joints have been identified as a critical factor in making the hexayurt constructible and providing overall stability.

The novel concept of using block joints in this way for structural applications, makes their analysis in line with structural design codes difficult and the results somewhat ambiguous. It was hence necessary to provide clarity to those results through laboratory testing. This also allowed practical observations to be made which will ultimately aid in achieving an optimum design.

Section 6.2 has highlighted the magnitude and type of forces which act on the hexayurt. From this data, a preliminary round of tests were developed in order to identify the key variables which contribute to the failure of the joints. Following the observations made, a code based joint design was devised and a refined second phase of testing was developed. The data and observations have subsequently been evaluated against the values obtained in the joint design and conclusions have been drawn.

### 6.4.2 Preliminary Testing Introduction

The analysis of the Hexayurt structure from section 6.2, has identified that the joints act in a combination of *tension* and *shear* to enable the structure to stand under its various loading conditions. This provided a basis for developing the preliminary round of testing.

Eurocode 5 - Timber Design, identifies failure modes for axially loaded screws in joints (used without steel plates) in clause 8.7.2, as:

- The withdrawal failure of the threaded part of the screw
- The pull through of the screw head
- The tensile failure of the screw
- The buckling failure of the screw when loaded in compression

BS 5268-2: 1996 - Timber Design, provides guidance that laterally loaded joints acting in pure shear will undergo shear failure of the weakest element of the joint, which in this case will be either the engineered timber board, or the timber block joint.

There are various codes which exist, providing guidance in testing for the identified failure modes directly:

- BSEN 1380: 2009 Timber Structures - Test Methods - Load Bearing Nails, Screws, Dowels and Bolts
- BSEN 409: 2009 Timber Structures - Test Methods - Determination of Yield Moment for Dowel Type Fasteners
- BSEN 1383: 1999 Timber Structures - Test Methods - Pull through resistance of Timber Fasteners
- BSEN 383: 2007 (E) - Timber Structures - Test Methods - Determination of Embedment Strength for Dowel Type Fasteners
- BSEN 1382: 1999 - Timber Structures - Test Methods - Withdrawal Capacity of Timber Fasteners
- BSEN 1537: 2009 - Timber Structures - Test Methods - Torsional Resistance of Driving in Screws

In the interests of time, and to create a concise set of results; the above codes have been used as reference from which to develop three preliminary tests which recreate the real life loading scenarios. Following this rationale, allowed for the weakest point failure mode to be observed as opposed to testing for each mode separately.

Overall guidance for the testing procedure for timber joints was taken from BSEN 2681:1991 Timber Structures - Joints made with mechanical fasteners - General principles for the determination of strength and deformation characteristics. However, it is ultimate joint strength which is critical over the deformation of joints and this priority has been reflected in the tests accordingly. All codes have been referenced where referred to in the testing process.

6.4.3 Manufacturing Test Samples:

According to BSEN 2681: 1991 Clause 6, the form and dimensions of test joints should be realistic so that the necessary information about the strength and deformation in service can be obtained. The joints for preliminary testing were manufactured using 300mm x 300 mm board cuts and 4" x 2" CLS blocks, both cut using a table saw. This was determined to be enough board material to efficiently measure the joint properties.


**Fig 6.4.3.1:** Example Preliminary Test Joint

Screws in the joints were spaced in accordance with Table 8.6 of Eurocode 5 - Timber Design, with the exception of the dimension $a_{1,CG}$ 'minimum end distance to the centre of gravity of the threaded part of the screw in the member'. This has been discussed in greater detail in appendix C.

The moisture content of the timber and boards used was not investigated using the kiln drying method prior to testing, as specified in various British Standards and Eurocodes. However, a content of 15% was assumed throughout, which is an average for timber stored inside, in the UK. From section 5.2.4 materials, it was stated that as a worst case, the

Hexayurt must be expected to be exposed to BS5268 service class 3 conditions. This assumes a moisture content of between 20% and 30%, where fibre saturation occurs.

For the purposes of design and testing, as a worst case, it shall be assumed that the highest category moisture content consistently exists in the timber block joints at between 20% and 30% (where fibre saturation occurs). According to BS 5268 part 2 for timber design, this is considered as service class 3. Taylor (2010: 526) describes how, at common moisture contents in the region of 15%, the strength will be approximately 40% higher than at the saturation point. It is hence necessary to apply a reduction factor of the results obtained in the lab by 20% to take into account the differing moisture content in the field.

From the constructability test observations, it is clear that the joints constructed for testing in a laboratory environment will be of a great deal higher quality than those constructed in the field. This must be taken into account by identifying a relevant reduction factor in joint capacity. By engineering judgement, the capacity of the joints should be reduced by a further 30% than found by laboratory testing. However, It remains necessary that a high standard is maintained in the production of the laboratory joints in the interests of obtaining reliable and comparable data.

**Fig 6.4.3.2:** Manufactured Test Joints in the Laboratory

## 6.5 PRELIMENARY TESTING PROCEDURES

6.5.1 Preliminary Test 1; Pure Shear:

To prepare the test joints for the pure shear tests, a 4 x 2" length of CLS was screwed to the board that the screws enter the block joint perpendicular to the grain, to aid in clamping the sample to the rig.

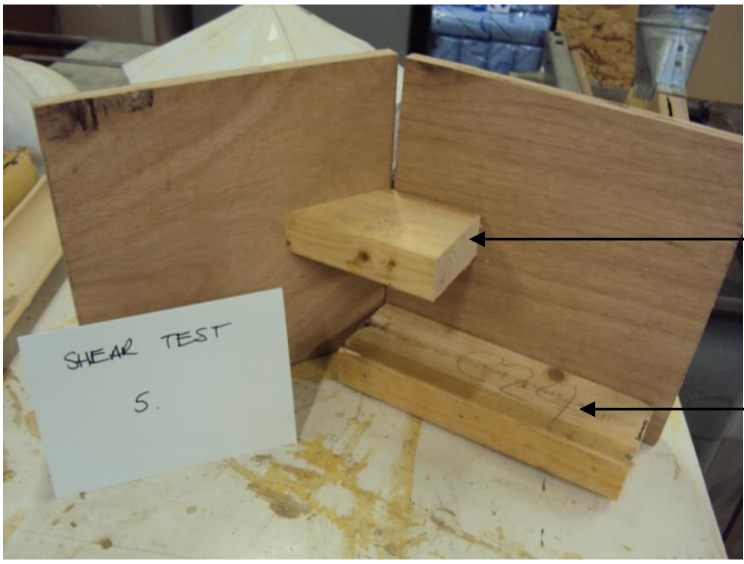


**Fig 6.5.1.1:** Photograph Showing Temporary Clamping Block

The joint samples were then individually clamped against a 50mm deep rectangular hollow section to provide clearance for movement under shear load; and subsequently clamped to a pre-constructed frame of I beams. Shear was induced in the joint by a hydraulic jack, launching from the lower part of the frame rig, pushing on the overhung board. Anticipating that the screws driven into the partial end grain would be weakest, this part of the joint was loaded.

A load cell, attached to a computer through a RDP modular interface was placed under the hydraulic jack. The load reading from the cell was logged at 1 second intervals using a Microsoft Excel macro program.

The weight of the hydraulic jack was measured on a laboratory top pan balance at 6.3kg. It was necessary to subtract this from the final load readings.

It was anticipated that movement would be recorded in line with loads through the same interface and program using LVDT's, however no suitable method could be found to attach them to the samples and rig. This results in a departure from BSEN 26891: 1991, joint slip can only be observed visually.

In a further departure from the recommendations of BSEN 26891: 1991, the load is applied manually through the lever of the hydraulic jack. This is due to equipment not being available in the laboratory to apply computer controlled load in this manner. This results in Clause 8.2, Application of Load, not being possible. The laboratory apparatus used however, was capable of measuring load to the level of accuracy as stipulated by clause 8.4.

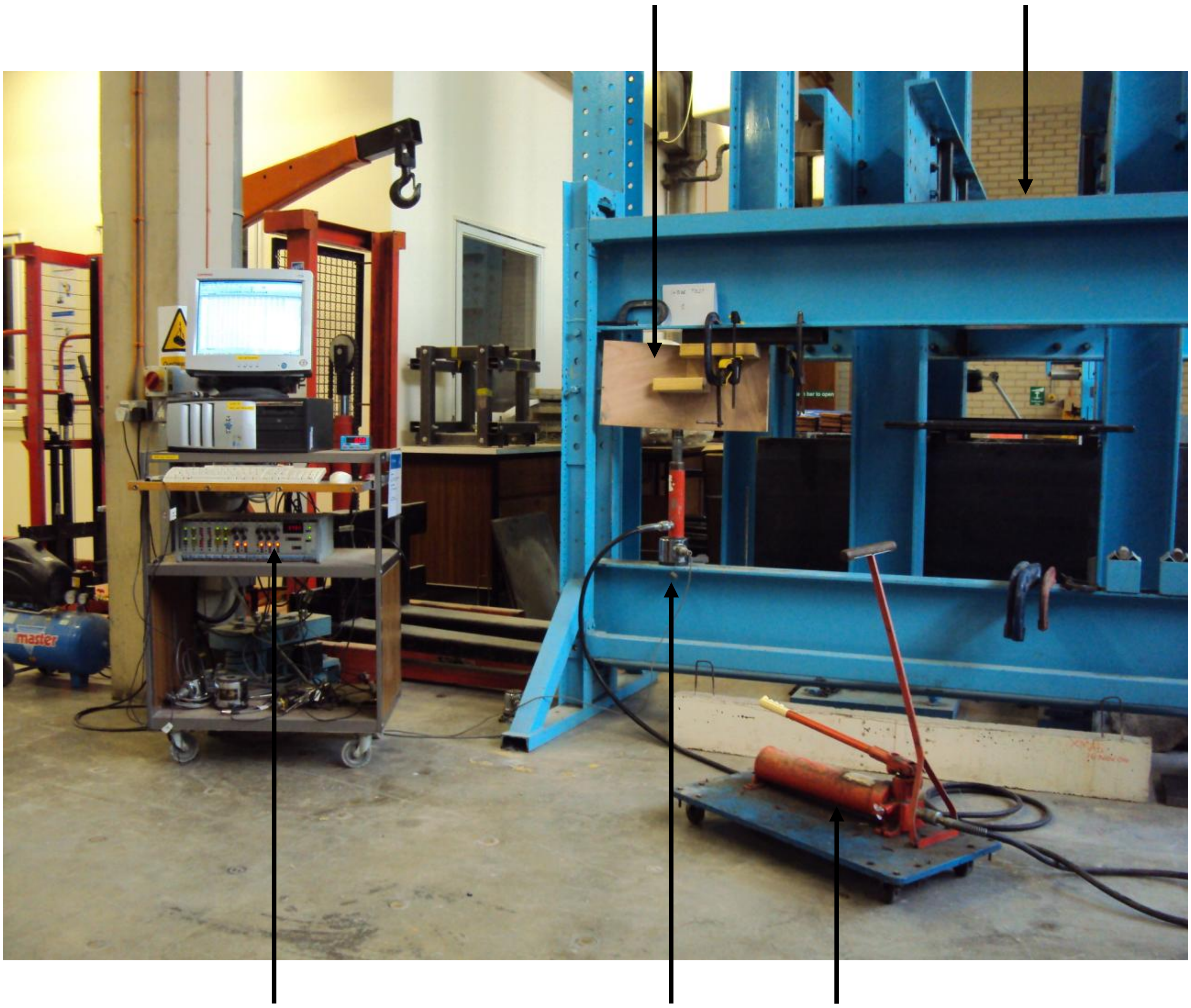


**Fig 6.5.1.2:** Photograph Showing Shear Test Set Up

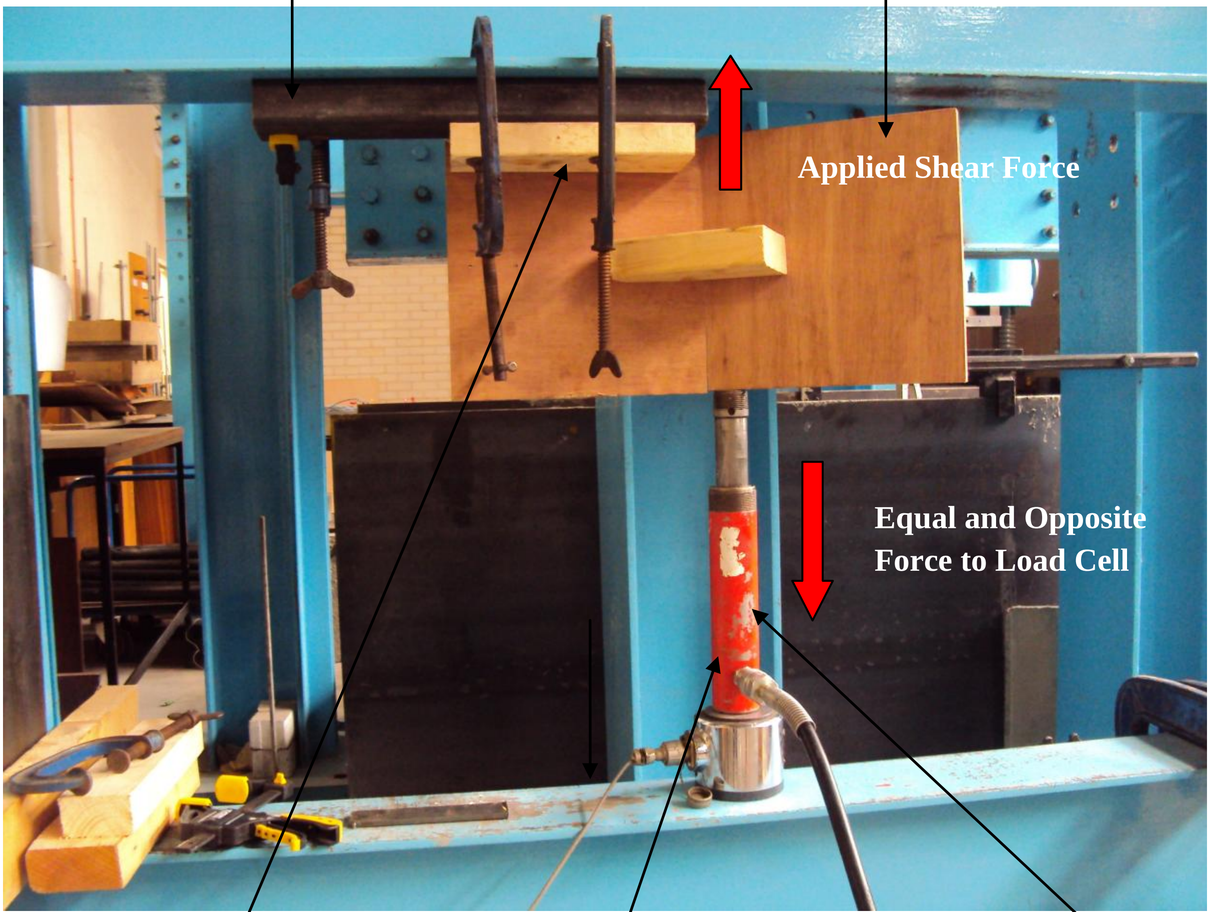


**Fig 6.5.1.3:** Photograph Showing Shear Test Set Up and Force Directions

6.5.2 Preliminary Test 2; Hydraulic Jack Tension:

The second preliminary test was developed in an attempt to recreate the loading experienced by the eaves joint, where uplift occurs due to suction from the wind.

The restraint provided by the wall joints was replicated by clamping the board with laterally fixed block joint screws to the flange of a test rig beam. This left the other board, replicating the roof, free to rotate. A hydraulic jack was used, launched from a side support plate to apply lateral force the replicated roof board. Load was applied until failure occurred. The load output was recorded by placing a load cell behind the hydraulic jack and logging through a RDP interface and computer, as used for test 1, section 6.5.1.

The joint samples were modified with a temporary block screwed through the dummy roof board, to allow load to be applied laterally.

Consideration was given to the conditioning of the test specimens as advised by clause 5 of BSEN 26891: 1991. However, as with the shear test in section 6.5.1, computer controlled application of load was not possible, resulting in a departure from Clause 8.2 for application of loading procedure. Again, no suitable method for attaching LVDT instruments for the measurement of slip could be determined. Apparatus used was capable of displaying loading values to the tolerances stated in clause 8.4.

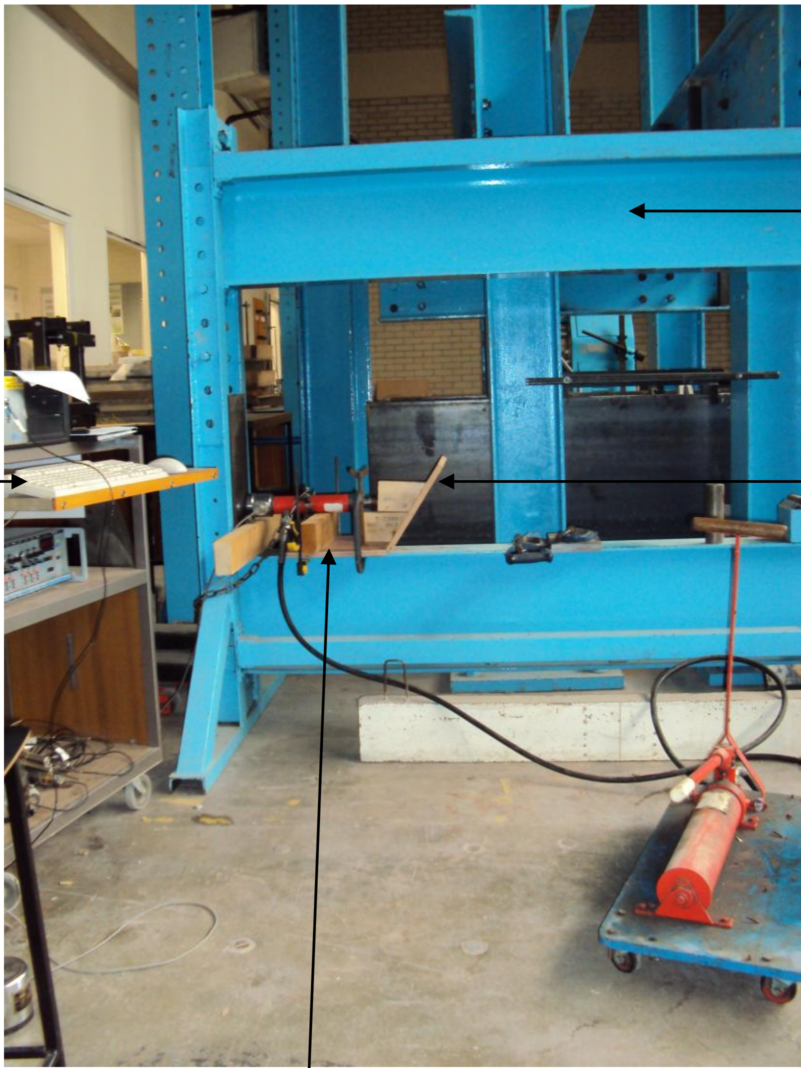


**Fig 6.5.2.1:** Hydraulic Tension Test Apparatus

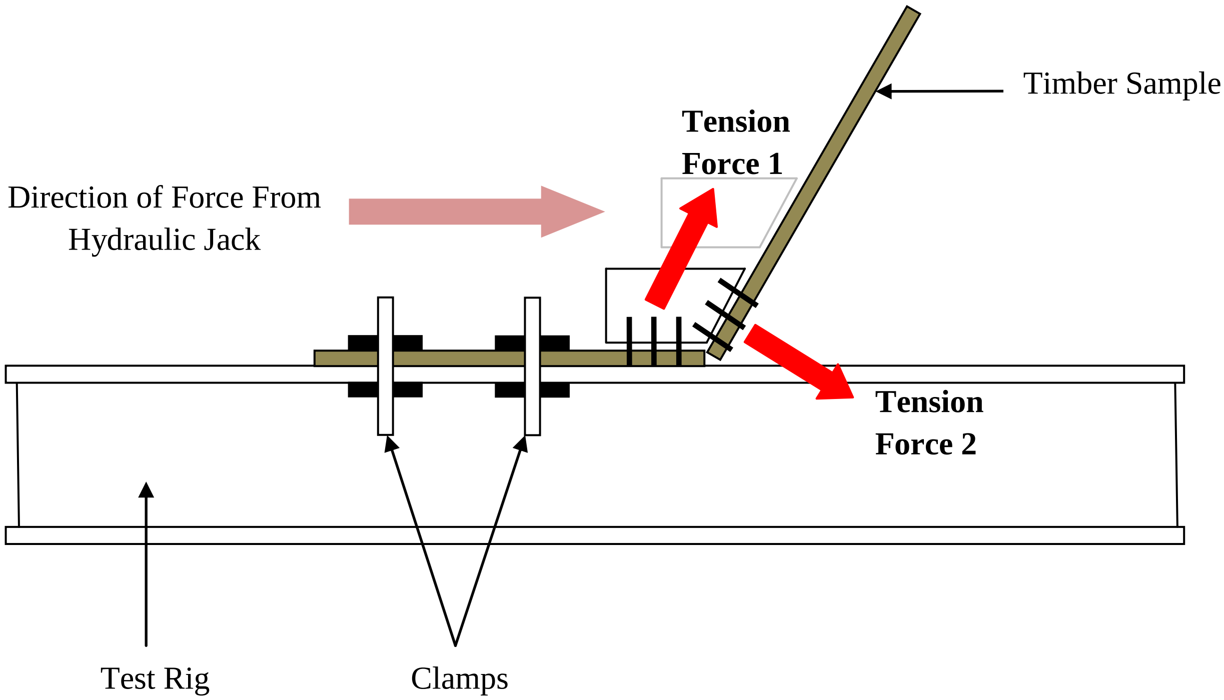


**Fig 6.5.2.2:** Section Diagram of Hydraulic Jack Tension Test, Showing Forces

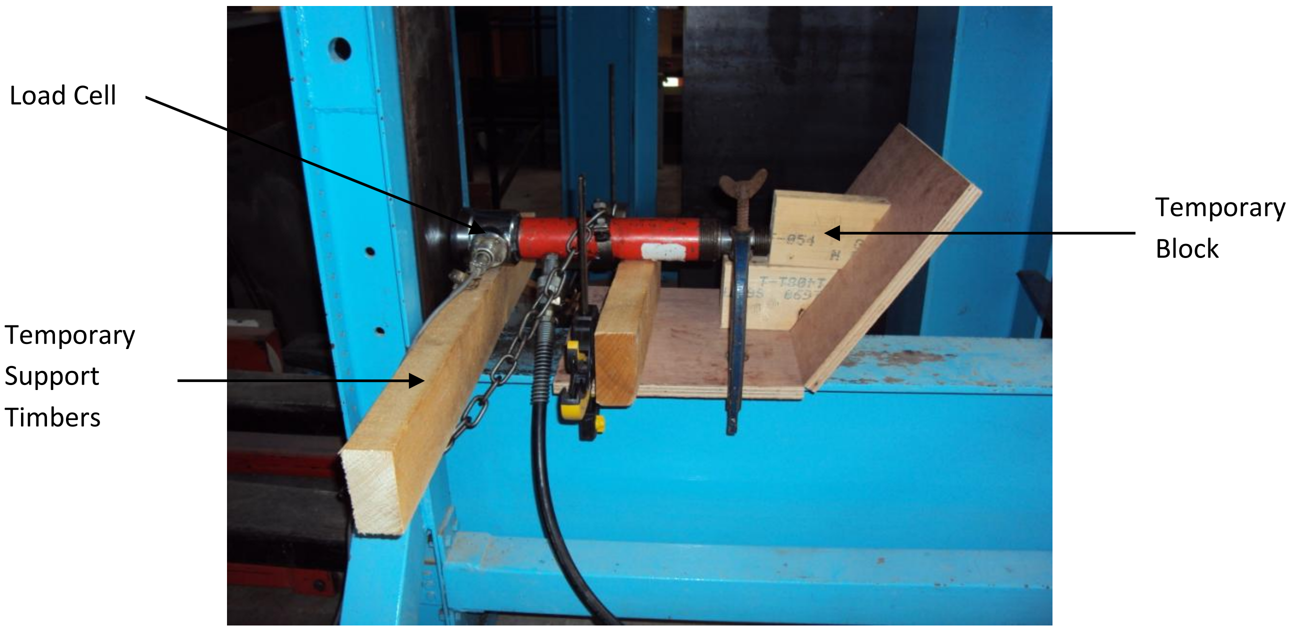


**Fig 6.5.2.3:** Hydraulic Tension Test Apparatus

6.5.3 Preliminary Test 3; JJ Lloyd Tension Test:

In order to replicate the evenly applied tension experienced by both the wall and roof joints due to wind loading, the third preliminary test was conducted using a computer controlled tension machine, with built in extension measuring capability.

The machine used for the test, manufactured by JJ Lloyd, has a tensile loading capacity of 100kN. The load and extension measuring capabilities comply with the requirements of clause 7 in BSEN 26891: 1991. The full specification for the machine is available at www.lloyd-instruments.co.uk.

The joint samples were modified to fit the machine, by drilling a 20mm diameter hole at the centre of each board, 40mm in from the edge. Steel pins were fed through the holes in order to secure them to the jaws of the machine.

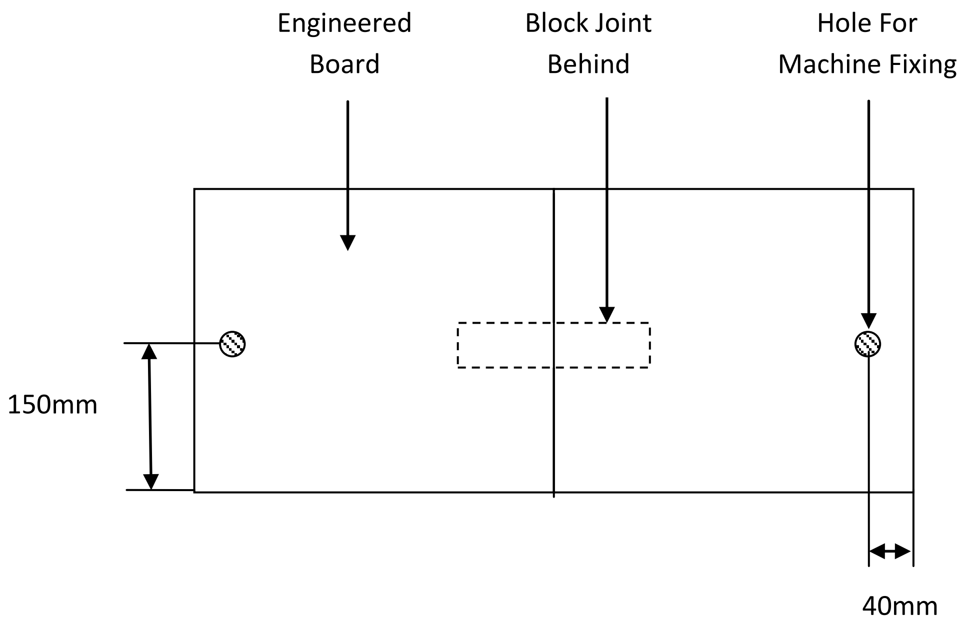


**Fig 6.5.3.1:** Elevation Diagram of Joint Sample Showing Location of Drilled Holes

When fitted to the machine, the sample was loaded in tension at a rate of 10mm/minute until failure point was reached.  No preload was applied, and the machine ceased to apply further load when a drop of 50% in capacity was reached.

Whilst the JJ Lloyd has the capability to apply load as recommended by clause 8.2 of BSEN 26891: 1991, the loading rate of 10mm per minute was deemed to be slow enough to not require this method.


**Fig 6.5.3.2:** JJ Lloyd 100 Testing Machine and Computer

**Fig 6.5.3.3:** JJ Lloyd 100 Testing Machine and Joint Sample

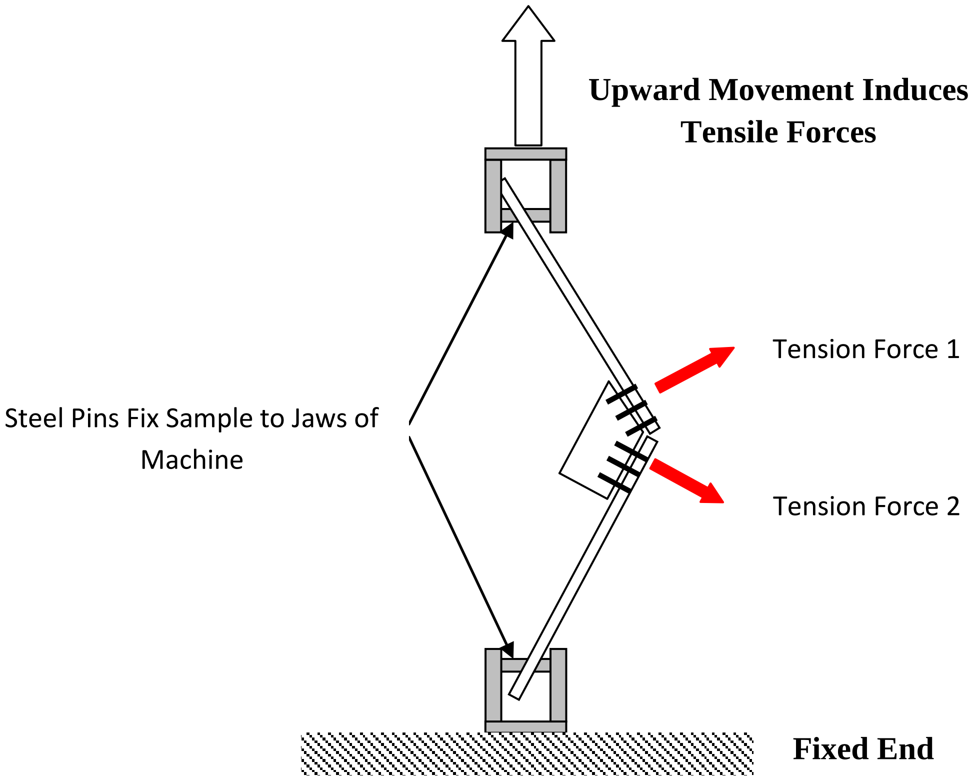


**Fig 6.5.3.4:** Diagram of JJ Lloyd Test Set Up and Direction of Forces Induced

6.5.4 Results:

The initial research has identified a wide number of joint variables to be designed and tested, in order to reach acceptable and valid conclusions as to the structural stability of the Hexayurt in the Haitian environment. These include force magnitude and type, board type, board thickness, block joint timber grade, block joint size, number of screws, and length and diameter of screws. This presents too wide a scope for a preliminary phase of testing, and hence it has hence been necessary to test a small number of joints at the extremes of some of the variables, in order to identify the key variables with which to progress a more detailed and concise round of testing.

A testing matrix was developed, and the most significant joints were selected and manufactured. Various tests types were conducted in line with section 6.5.1 to 6.5.3, the results of which are presented and discussed below.

Since the Hexyurt is designed as a temporary structure for use in emergency situations, the 'slip' of the joints under loading is not as critical as in a larger framed structure or roof, on which the design codes are based; and it is in fact the ultimate load capacity of the joint which is critical. Clause 8.4 of BSEN 26891: 1991 states that the maximum load capacity of each sample ($F_{max}$) shall be taken at a slip value of 15mm. Owing to the nature of the structure, and the unrealistically low $F_{max}$ values that would be obtained, particularly with the reduction factors that have been identified, this has been ignored. The reduction factors of 20% for potentially high moisture content and 30% for poor workmanship have been applied to the results, producing the tested capacity of the joint.

Results Table Key for Failure Modes:

# 1 = Shear failure of block joint

# 2 = Block joint split below pointside of screw

# 3 = Screw head pull through board

| Board Type | Force Applied | Board Thickness | Joint Grade | No of Screws | Result (kN) | Modified Load (kN) | Failure Mode |
|---|---|---|---|---|---|---|---|
| Plywood (WBP) | Shear | 9mm | C16 | 4 | | | |
| | | | | 6 | | | |
| | | | C24 | 4 | | | |
| | | | | 6 | | | |
| | | 18mm | C16 | 4 | | | |
| | | | | 6 | | | |
| | | | C24 | 4 | | | |
| | | | | 6 | 1.02 | 0.51 | 1 |
| | Tension (Hydraulic Jack) | 9mm | C16 | 4 | | | |
| | | | | 6 | | | |
| | | | C24 | 4 | | | |
| | | | | 6 | | | |
| | | 18mm | C16 | 4 | | | |
| | | | | 6 | 0.42 | 0.21 | 2 |
| | | | C24 | 4 | | | |
| | | | | 6 | | | |
| | Tension (JJ Lloyd) | 9mm | C16 | 4 | 1.14 | 0.57 | 3 |
| | | | | 6 | | | |
| | | | C24 | 4 | | | |
| | | | | 6 | | | |
| | | 18mm | C16 | 4 | | | |
| | | | | 6 | | | |
| | | | C24 | 4 | | | |
| | | | | 6 | 1.16 | 0.58 | 2 |

Note: Screw type used was 10 x 2" throughout

**Fig 6.5.4.1:** Testing Matrix for Plywood, Showing Results Obtained for Chosen Tests

| Board Type | Force Applied | Board Thickness | Joint Grade | No of Screws | Result (kN) | Modified Load (kN) | Failure Mode |
|---|---|---|---|---|---|---|---|
| OSB (3) | Shear | 9mm | C16 | 4 | | | |
| | | | | 6 | | | |
| | | | C24 | 4 | | | |
| | | | | 6 | | | |
| | | 18mm | C16 | 4 | | | |
| | | | | 6 | | | |
| | | | C24 | 4 | | | |
| | | | | 6 | | | |
| | Tension (Hydraulic Jack) | 9mm | C16 | 4 | 0.10 | 0.05 | 3 |
| | | | | 6 | | | |
| | | | C24 | 4 | | | |
| | | | | 6 | | | |
| | | 18mm | C16 | 4 | | | |
| | | | | 6 | | | |
| | | | C24 | 4 | | | |
| | | | | 6 | | | |
| | Tension (JJ Lloyd) | 9mm | C16 | 4 | | | |
| | | | | 6 | | | |
| | | | C24 | 4 | | | |
| | | | | 6 | | | |
| | | 18mm | C16 | 4 | | | |
| | | | | 6 | | | |
| | | | C24 | 4 | | | |
| | | | | 6 | | | |

Note: Screw type used was 10 x 2" throughout

**Fig 6.5.4.2:** Testing Matrix for Orientated Strand Board, Showing Results Obtained for Chosen Tests

6.5.5 Observations:

As predicted in section 6.5.1, the shear test led to a failure of the block joint around the screws, where the load is transferred. Perhaps less predictable however, was the failure occurring around the screws which were driven perpendicular to the grain and not through the semi-end grain which should be a great deal weaker. This highlights the unpredictability of natural materials and the need to conduct several tests in repetition in order to achieve an accurate output.

**Fig 6.5.5.1:** Photograph Showing Shear Failure of Block Joint Around Screws Driven Perpendicular to the Grain

The shallow depth of the failure suggested that, should a deeper screw be used, stress would be better able to be transferred into the block joint and a higher load achieved.

Both tension tests (see section 6.5.2 and 6.5.3) resulted in screw head pull through failures of 9mm thick OSB and Plywood board types.

**Fig 6.5.5.1:** Photograph Showing Screw Head Pull Through of 9mm OSB, Following Hydraulic Jack Tension Test

**Fig 6.5.5.2:** Photograph Showing Board Deformation and Screw Head Pull Through for 9mm Plywood, During JJ Lloyd Tension Test

**Fig 6.5.5.3:** Photograph Showing Rear View of Screw Head Pull Through for 9mm Plywood, Following JJ Lloyd Tension Test

It is possible to deduce that, when using 9mm board, screw head pull through is likely to be the critical failure mode. This occurred at far lower loads in OSB than plywood. The use of a thicker board or using washers to distribute stress would increase the capacity of the joint in this respect.

When 18mm boards were used, the critical failure mode was a brittle tensile split, parallel to the grain of the block joint, occurring just below the pointside of the screws. On both occasions, this failure occurred directly under the screws driven perpendicular to the grain. Again, the requirement for better stress distribution through a deeper screw is highlighted.

When the joint samples were placed under tension, the strength grade of the block appeared to make little difference to the ultimate capacity.

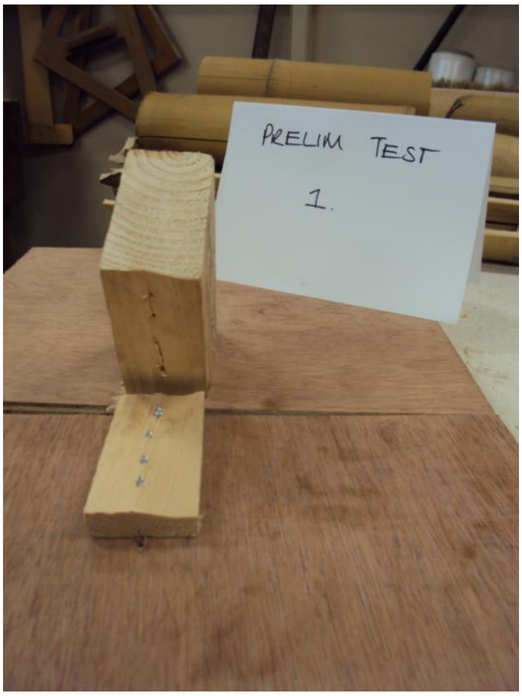


**Fig 6.5.5.4:** Photograph Showing Hydraulic Jack Tension Test Block Joint Failure

**Fig 6.5.5.5:** Photograph Showing JJ Lloyd Tension test Block Joint Failure

## 6.6 JOINT DESIGN

From the observations made during the initial testing phase and by drawing comparisons with joint loading results from the static analysis, the following factors were identified as critical to be designed and tested in order to achieve the optimum, efficient design:

- Design and test using both OSB and Plywood
- Proceed assuming 18mm board thickness only for walls and roof
- Vary block joint thickness between 4 x 2" CLS and 5 x 2" CLS
- Use only C16 CLS timber for block joints
- Vary number of Screws in the joint between 6 and 8
- Vary screw diameter and depth between 4.17mm dia., 3" deep and 4.88mm dia., 2" deep respectively
- Vary the use of washers

Using this data, two different joint designs were produced for the walls, eaves and roof joints. The code based design and joint layout can be viewed in appendix C at the rear of the project.

Fig 6.6.1 shows a matrix produced to summarise the results of the design exercise.

| Joint | Block Joint Size | No of Screws | Screw Type | Shear Load Applied (kN) | Tensile Load Applied (kN) | Capacity (kN) | Number of Joints required [1] |
|---|---|---|---|---|---|---|---|
| Wall | 4 x 2" | 6 | 10 x 2" | 5.4 | | 2.5 | |
| | | | | | 3.0 | 0.7 | 5 |
| | 5 x 2" | 8 | 8 x 3" | 5.4 | | 2.7 | |
| | | | | | 3.0 | 1.1 | 3 |
| Eaves | 4 x 2" | 6 | 10 x 2" | | 3.2 | 0.7 | 5 |
| | | | | | | | |
| | 5 x 2" | 8 | 8 x 3" | | 3.2 | 1.1 | 3 |
| | | | | | | | |
| Roof | 4 x 2" | 6 | 10 x 2" | 6.4 | | 2.5 | |
| | | | | | 3.2 | 0.7 | 5 |
| | 5 x 2" | 8 | 8 x 3" | 6.4 | | 2.7 | |
| | | | | | 3.2 | 1.1 | 3 |

**Notes:**

1) Number of joints required shows the critical value worst case

2) Data for designing for use of washers not available, observe during testing phase only

**Fig 6.6.1:** Table Showing Results of Code Based Joint Design Exercise (See appendix C)

## 6.7 FINAL TESTING PHASE

### 6.7.1 Introduction

In order to corroborate the values obtained from the code based joint design and make practical observations with regards to construction and failure modes, a final testing phase was carried out using the joints from section 6.6. The tests used were the hydraulic shear test, (see section 6.5.1) and the JJ Lloyd tension test, (see section 6.5.3). The hydraulic tension test was omitted from the final testing phase on the basis that is could not be controlled via the codes for timber joint testing.

It was not possible on the grounds of material supply and time to carry out more than one test per scenario, however as the variations are small, anomalies were easily identifiable.

6.7.2. Shear Test Results

Results Tables, Key for Failure Modes:

# 1 = Shear failure of block joint

# 2 = Block joint split below pointside of screw

# 3 = Screw head pull through board

# 4 = Board snapped at outer screw line

# 5 = Screw pull out of block joint

#6 = Failure due to imperfection in block joint timber

The reduction factors of 20% for potentially high moisture content and 30% for poor workmanship have been applied to the results, producing the tested capacity of the joint.

Shear Testing:

| Board Type | Joint Angle | Block Joint Size | No of Screws | Type of Screws | Washers | Result (kN) | Modified Load (kN) | Failure Mode |
|---|---|---|---|---|---|---|---|---|
| Plywood (WBP) | 120 | 2 x 4" CLS | 6 | Gr 10 x 2" | N | 1.624 | 0.812 | 1 |
| | | | | | Y | 2.514 | 1.257 | 1 |
| | | 2 x 5" CLS | 8 | Gr 8 x 3" | N | 3.157 | 1.579 | 1 |
| | | | | | Y | 1.551 | 0.776 | 1 |
| | 150 | 2 x 4" CLS | 6 | Gr 10 x 2" | N | 2.193 | 1.097 | 1 |
| | | 2 x 5" CLS | 8 | Gr 8 x 3" | N | 5.194* | n/a | 1 |
| OSB (3) | 120 | 2 x 4" CLS | 6 | Gr 10 x 2" | N | 2.836 | 1.418 | 1 |
| | | | | | Y | 1.202 | 0.601 | 1 |
| | | 2 x 5" CLS | 8 | Gr 8 x 3" | N | 2.670 | 1.335 | 1 |
| | | | | | Y | 3.910 | 1.995 | 1 |
| | 150 | 2 x 4" CLS | 6 | Gr 10 x 2" | N | 1.982 | 0.991 | 1 |
| | | 2 x 5" CLS | 8 | Gr 8 x 3" | N | 2.030 | 1.015 | 1 |

* Result is identified as an anomaly

**Fig 6.7.2.1:** Table Showing Final Testing Matrix and Shear Test Results

### 6.7.3 Shear Test Observations:

The 150˚ roof joint, constructed from 5 x 2" CLS using 8 No 8 x 3" screws, produced an abnormally high failure load of 5.194kN. Following an inspection of the test rig, it was discovered that the correct amount of clearance to allow the joint to move freely was not allowed. This caused contact between the joint and the rectangular hollow section spacer, providing a great deal of restraint to the joint prior to failure. As shown in the figure 6.7.2.1, this result has not been considered in the comparison between laboratory observed results and results obtained in the code based design.

**Fig 6.7.3.1:** Photograph Showing Shear Test With Abnormally High Failure Load

**Fig 6.7.3.2:** Photograph Showing Contact Between Board of Joint and Rectangular Hollow Section Spacer

The presence of washers appeared to have no impact on the failure load of the joints in shear, and the results varied between slightly stronger and slightly weaker with washers in a random fashion. Since in this scenario, the screws are loaded laterally, it was not perceived that the washers would increase joint strength.

No numerical correlation could be determined from the samples tested, as to the effect of the engineered timber board type (OSB or plywood). Since all joints experienced failure mode from shear in the block joint, it is assumed that the board type used has no effect on the shear capacity of the joint. However, joints using 2 x 5 " CLS block joints with 8 x 10 screws, were observed to be stronger in shear by approximately double when plywood was used as the board and only slightly stronger when OSB was used. Despite this variation in capacity, the eventual failure mode was brittle shear failure of the block joint throughout.

**Fig 6.7.3.3:** Photograph Showing Typical Failure in Block Joints Due to Shear Load

All of the joints demonstrated a high level of flexibility prior to failure in shear, in particular those constructed from 5 x 2" CLS block joints with 8 x 3" screws. The brittle failure at lower strength is assumed to have been avoided by the presence of a greater number of deeper screws, allowing better distribution of stress. This provides a positive outcome for the purposes of seismic design.

**Fig 6.7.3.3:** Photograph Demonstrating Degree of Joint flexibility Observed During Tests

There was not a strong enough correlation between the results obtained in the joint design exercise and those found by the physical testing, to draw direct comparisons and conclusions. It was found that for every joint test that matched or exceeded the design calculations, another very similar one came far below. This highlights the variability in the quality of timber samples, and strengthens the argument to conduct a wider range of physical testing to achieve more meaningful results.

### 6.7.4 JJ Lloyd Tension Test Results:

| Board Type | Joint Angle | Block Joint Size | No of Screws | Type of Screws | Washers | Result (kN) | Modified Load (kN) | Ext. at Failure (mm) | Failure Mode |
|---|---|---|---|---|---|---|---|---|---|
| Plywood (WBP) | 120 | 2 x 4" CLS | 6 | 10 x 2" | N | 1.615 | 0.809 | 20.9 | 6 |
| | | | | | Y | 1.730 | 0.865 | 18.4 | 5 |
| | | 2 x 5" CLS | 8 | 8 x 3" | N | 3.757 | 1.788 | 43.4 | 3 |
| | | | | | Y | 2.567 | 1.284 | 22.4 | 4 |
| | 150 | 2 x 4" CLS | 6 | 10 x 2" | N | 3.626 | 1.813 | 52.6 | 3 |
| | | 2 x 5" CLS | 8 | 8 x 3" | N | 7.456 | 2.728 | 42.4 | 5 |
| OSB (3) | 120 | 2 x 4" CLS | 6 | 10 x 2" | N | 1.890 | 0.945 | 20.7 | 4 |
| | | | | | Y | 1.139 | 0.570 | 11.6 | 5 |
| | | 2 x 5" CLS | 8 | 8 x 3" | N | 2.915 | 1.458 | 88.1 | 3 |
| | | | | | Y | 2.384 | 1.192 | 22.7 | 4 |
| | 150 | 2 x 4" CLS | 6 | 10 x 2" | N | 5.522 | 2.761 | 35.2 | 5 |
| | | 2 x 5" CLS | 8 | 8 x 3" | N | 5.057 | 2.529 | 41.8 | 5 |

**Fig 6.7.4.1:** Table Showing Final Testing Matrix and Tension Test Results

### 6.7.5 JJ Lloyd Tension Test Observations:

The tension tests provided a much more stable set of results, as a basis for the analysis and comparison with the joint design results. It can first be observed that the Plywood did not achieve significantly higher tensile capacities than the OSB, which was unexpected given the much lower failure load in the preliminary round of testing using 9mm thick OSB and plywood, for which the failure modes were both screw head pull through.

The most common mode of failure in tension was a result of the screw pulling out of the block joint, although as would be expected, this did not always occur in the screws driven through the semi-end grain first. The modes of failure in general however ranged between Screw head pull through board, board snapping at outer screw line, screw pull out of block joint and failure due to imperfection in block joint timber.

**Fig 6.7.5.1:** Photograph Showing Failure Mode #3, Screw Head Pull Through Failure - in OSB and Plywood Joint Samples

**Fig 6.7.5.2:** Photograph Showing Failure Mode # 4, Board Snapping at Outer Screw Line - in Plywood Joint Sample

**Fig 6.7.5.3:** Photograph Showing Failure Mode # 4, Board Snapping at Outer Screw Line - in OSB Joint Sample


**Fig 6.7.5.4:** Photograph Showing Failure Mode # 5, Screw Pull Out of Block Joint - in OSB and Plywood Joint Sample

**Fig 6.7.5.5:** Photograph Showing Failure Mode # 6, Failure Due to Imperfections in Timber Block Joint - in OSB Joint Sample

The tested tensile load capacity tended to exceed the design values by approximately 0.1kN in general. This is encouraging, as the code based joint design is conservative and appears to prove the stability of the Hexayurt. However, these results should be approached with caution owing to the departure from timber joint testing code BSEN 26891: 1991. Further investigation with regards to the significance of joint slip in a structure used for this purpose *may* be required.

The 2 x 5" block joints with 8 No, 8 x 3" screws provided approximately twice the tensile capacity than the 2 x 4" blocks with 6 No, 10 x 2" screws for 120˚ block joints. There was no significant difference in strength between the two for the 150˚ roof joint. This was due to the small 30˚ angle difference between boards, resulting in the screws being pulled practically perpendicular to the grain of the block joint, producing high failure values.

The largest extension readings occurred when the failure mode was screw head pull through, at readings as large as 88.1mm, however the vast majority of failures occurred within 5mm of the 15mm maximum as stipulated by the code. There didn't appear to be any correlation between joint type and large extension values, but the lowest extension values occurred with the presence of washers when a brittle failure mode in the board was generally induced. However, the inclusion of the washers did not raise the failure load and in one case it was worse.

The joint design process highlighted how tension is the critical failure mode at each of the three joint types which make up the Hexayurt (See fig 6.6.1). Since the joints appeared to perform better in practice, than in the code based design process, it is possible to tentatively state that the Hexayurt will stand in the Haitian environment using only timber block joints, if:

- *Either* 3 No 5 x 2" block joints with 8 No 8 x 3" screws
- *Or* 5 No 4 x 2" block joints with 6 No 10 x 2" screws

are used along each joint.

# CHAPTER 7 - CONCLUSIONS AND RECOMMENDATIONS

## 7.1 CONCLUSION

By a direct comparison of this report against the aim identified in chapter 1, the conclusion is as follows:

> 'The Hexayurt can be made structurally adequate for use as a transitional disaster relief shelter Haiti'

Following the development of understanding for the structural principles of the Hexayurt, and the identification of constructability and material availability as key parameters to its success in the field; the aim was further refined in chapter 5 to determine the structural adequacy using only screwed timber block joints, omitting the use if glue and straps. Whilst the physical testing in shear produced inconsistent results, it is still possible to further the conclusion on the basis of the detailed code based joint design and tension tests to:

> 'The Hexayurt can be made structurally adequate, using only screwed timber block joints, for use as a transitional disaster relief shelter Haiti'

However this statement is based on a number of parameters which must be observed in order for it to stand true:

- 18mm thick OSB(3) or Plywood (WBP) board is used
- *Either* 3 No 5 x 2" block joints with 8 No 8 x 3" screws , *Or* 5 No 4 x 2" block joints with 6 No 10 x 2" screws are used along each board joint throughout.
- Screws are spaced as closely to Eurocode 5 requirements as possible in field environment (reduction factors applied)

In a further variable identified for testing, washers were not deemed to provide any benefit in terms failure load values in tension or shear.

The high flexibility of the joints prior to failure observed, together with the seeming spare tensile capacity in the joints provides an encouraging sign for the capability of the unit under seismic loading. However no analysis was produced with regards to the loads which the Hexayurt may undergo, nor what magnitude of earthquake it may be capable of resisting.

In order to reach the conclusions in this report, the environmental conditions of Haiti were investigated. As discussed in chapter 4, the discovery of hard data with which to carry out numerical analysis, particularly with respect to wind speeds, proved difficult for Haiti as no building codes currently exist. It is therefore anticipated that the collaboration of the various forms of data necessary for this project will provide a useful reference point for similar investigations in the future.

## 7.2 RECOMMENDATIONS

The process of conducting the research included in this report has resulted in the identification of the following recommendations for further research:

1. Further investigate constructability, in order to provide best practice for mass production
2. Carry out analysis to determine holding down capacity of ground anchors
3. Conduct fire assessment/design to EC5 Timber Design, Part 1-2 General - Structural Fire Design
4. Carry out in depth analysis/testing with regards to seismic loading
5. Develop further understanding of the effects of a potential cyclone
6. Modify laboratory tests to be more in line with codes

7. Design and test likely upgrades such as window openings to ensure stability is not compromised.
8. Analyse in depth, the potential failure of individual panels due to wind, in particular the roof.
9. Carry out design of roof panel seam
10. Investigate benefit of using water resistant treated plain timber block joints
11. Calculate overall design life in Haitian environment
12. Provide detailed cost comparison of materials to achieve most economical design

Other more general recommendations which have been presented during the course of the project are as follows:

1. Work to further develop the design with the input of the local affected population
2. Assess the unit against habitability standards as listed in The Sphere Standards.
3. Explore potential of increasing size of hexayurt by joining/including infill panels, and assess how the structure is affected
4. Assess suitability of the Hexayurt for use in other disaster prone/affected regions around the world