Design of an Earthquake Proof One Family House
A house in alternative construction material, made for slum areas in Medellin, Colombia

Bachelor Degree Project in Mechanical Engineering - Development Assistance

30 ECTS
Spring term 2007

Anna Fabisch
Anders Karlsson

Supervisor: Ph. D. Tobias Andersson
Examiner: MSc. Kent Salomonsson
Abstract

One of mankind’s most important needs is the need for shelter. All around the world people live in lack of this basic need. Colombia is a South American country heavily burdened by civil war for many years. This has led to that many people have moved to the larger cities with large slum areas and bad living conditions. This thesis is aiming to give a solution to the problem with bad housing and it is performed in cooperation with Ankarstiftelsen. Ankarstiftelsen is a Swedish charity organisation that works with the suffering people in various places in Colombia.

This thesis examines the possibility to build a house in a sandwich technique with a core of rigid plastic foam and a skin material of fibre reinforced plastic. The construction should be as easy as possible to manufacture, and the construction is also intended to be self carrying. The final proposition is to build the house using polyurethane rigid foam as the core, and a glass fibre reinforced polyester as the skin. This combination combines good mechanical behaviour with a relatively low price.

Tests have been performed to evaluate the constructions ability to withstand some basic loads, with the help of computer aided engineering. The program that has been used to create a model is ProEngineer, and the application ProMechanica has been used to perform the analysis. The loads that have been tested are: gravity loads, wind loads, maintenance loads and earthquake loads. Colombia is located in the so called Pacific Ring of Fire, where earthquakes are a bitter reality. The Colombian building code is, as a result of this, much focused on the issue of earthquake safety. The Colombian building code has been used in order to create reliable earthquake testing models.

The authors come to the conclusion that the house is possible to build with the given data. However, further investigations regarding manufacturing techniques and practical tests have to be made before the house can be built in reality.
Acknowledgements

Thanks to everyone who helped us in completing this project. Special thanks to Ankarstiftelsen and Börje Erdtman. Thanks to Lennart Ljungberg for your willingness to share your expertise in plastics. Thanks to Lars Viebke for all the help in the composite area. Thanks to our supervisor Tobias Andersson for all your helpful advice. And last but not least, thanks to our understanding families for all your support.

Anna Fabisch & Anders Karlsson
# Table of contents

Abstract................................................................................................................................. i
Preface and acknowledgements........................................................................................... ii

Table of contents .................................................................................................................. 1

1 Introduction .......................................................................................................................... 3
  1.1 Partners .......................................................................................................................... 3
  1.2 Human needs ............................................................................................................... 3
  1.3 Colombia .................................................................................................................... 3
    1.3.1 Geographic facts .................................................................................................. 3
    1.3.2 Weather conditions ............................................................................................ 3
    1.3.3 Needs in Colombia .............................................................................................. 4

2 Project assignment .............................................................................................................. 4
  2.1 The house .................................................................................................................... 4
    2.1.1 Design ................................................................................................................. 4
    2.1.2 Construction ...................................................................................................... 5
  2.2 Location ..................................................................................................................... 5
  2.3 Delimitations .............................................................................................................. 5

3 Method ................................................................................................................................. 6
  3.1 Literature studies and internet .................................................................................... 6
  3.2 Computer Aided Engineering ................................................................................... 6

PART A: DESIGN AND CONSTRUCTION

4 The design of the house ...................................................................................................... 7
  4.1 Design Philosophy ..................................................................................................... 7
  4.2 Dimensions for the design plan ................................................................................. 7
  4.3 Wall thickness .......................................................................................................... 8

5 Sandwich construction ....................................................................................................... 8
  5.1 Skin material ............................................................................................................. 9
  5.2 Core ........................................................................................................................... 9

6 Plastic Composites ............................................................................................................. 10
  6.1 Matrix ....................................................................................................................... 10
  6.2 Fibres ....................................................................................................................... 11

7 Choice of material ............................................................................................................. 11
  7.1 Fire safety ............................................................................................................... 12
  7.2 Climate effect on the material .................................................................................. 13

8 Manufacturing techniques .................................................................................................. 13
  8.1 The Polyurethane rigid foam .................................................................................... 13
  8.2 The composite .......................................................................................................... 13

PART B: FINITE ELEMENT ANALYSIS OF REGULAR LOADS

9 The model ........................................................................................................................ 15

10 Loads ................................................................................................................................. 17
  10.1 Gravity Load ........................................................................................................... 17
  10.2 Maintenance Load .................................................................................................. 17
  10.3 Wind load ............................................................................................................... 17

11 Constraints ......................................................................................................................... 18
12 Material Properties........................................................................................................ 19
  12.1 Poisson’s ratio........................................................................................................ 19
13 Factor of Safety ............................................................................................................. 20
14 Analyses ...................................................................................................................... 21
15 Test results.................................................................................................................. 21

PART C: FINITE ELEMENT ANALYSIS FOR EARTHQUAKE DESIGN
16 Earthquake design........................................................................................................ 25
  16.1 Step 1 – The Elastic Acceleration Spectrum Diagram........................................ 26
  16.1.1 Seismic risk level and $A_a$ value................................................................. 26
  16.1.2 Soil characteristics, $S$ ................................................................................. 26
  16.1.3 Importance factor, $I$.................................................................................. 27
  16.1.4 The creation of the elastic acceleration spectrum diagram.......................... 27
  16.2 Step 2 – The seismic forces ............................................................................... 28
  16.2.1 The seismic shear....................................................................................... 28
  16.2.2 The seismic force....................................................................................... 29
  16.3 Step 3 – Accidental torsion ............................................................................... 29
  16.3.1 Calculation of the accidental torsion.......................................................... 29
  16.4 Step 4 – Load combinations ............................................................................. 30
  16.5 Step 5 - Horizontal displacement and drift ..................................................... 31
  16.6 Step 6 - Stress caused by the seismic forces....................................................... 33
17 Conclusions ................................................................................................................. 35
18 Recommendations for further development and advice for implementation ... 36

References ..................................................................................................................... 37
APPENDIX I – Analysis of the stress in the core............................................................... 39
APPENDIX II - Tables and figures used for wind load calculations................................. 40
APPENDIX III – Factor of Safety.................................................................................... 42
APPENDIX IV - Test chart.............................................................................................. Error! Bookmark not defined.
APPENDIX V - Tables and figures used for earthquake load calculations....................... 44
APPENDIX VI - Calculations of the mass of the house......................................................... 47
APPENDIX VII – Modal analysis...................................................................................... 48
1 Introduction

This report is made as a final thesis in the Development Assistance Engineer program, at the University of Skövde, Sweden, which leads to a bachelor’s degree in science. The extent of the course is 20 Swedish university credits, (equivalent to 30 ECTS), which is the same as 800 working hours per person. The thesis starts with an introduction followed by three different parts dealing with the issues of; A) design and construction, B) general loads and C) earthquake loads. The thesis ends with conclusions and recommendations for further developments.

1.1 Partners

This thesis work is made in cooperation with the charity organisation Ankarstiftelsen, situated in Mölltorp, Sweden. The work of Ankarstiftelsen relies totally upon the efforts of volunteers. Ankarstiftelsen is mainly working with street children in Colombia and Brazil. Well digging in the Amazonas and work among prisoners, (missionary and social) are also examples of work done by Ankarstiftelsen. Ankarstiftelsen is the owner of a Swedish so called 90-account. This means that the organization is supervised by the Swedish organization for fund raising control, (Sv: Stiftelsen för Insamlingskontroll) [1].

1.2 Human needs

The human being has a lot of needs that needs to be fulfilled. To be able to respire, and to have food and water, are the two most important physical needs. The need for shelter is the third most important need for the human being. In many places around the world people live in shortage of this basic need. War, natural disasters and poverty are some factors that cause this lack of shelter [2].

1.3 Colombia

1.3.1 Geographic facts

Colombia is located in the northern parts of South America. There is great variation in altitude in the country, from sea level up to about 5 500 meters above sea level. This gives great variations in the climate. Earthquakes are also a bitter reality in the country, due to its location on the Pacific Ring of Fire. The Pacific Ring of Fire is a horse shoe shaped area, surrounding the pacific ocean, which is suffering from many earthquakes and volcanic activities. This sets demands on constructions, and the Colombian building code has strong regulations regarding earthquake safety. Since Colombia is a tropical country close to the equator, another factor that might need to be considered is the rich flora of bugs and animals [3].

1.3.2 Weather conditions

Colombia is a land with large differences in temperature. The great variation in the altitude of the country gives the country great variations in the weather. From hot lowland to colder mountains, and from the dry lowlands, with only 75 centimeters of rain per year, to the rainy southeast with about 500 centimeters of rain per year [3].
1.3.3 Human Needs in Colombia

Colombia has been heavily burdened by civil war for about 40 years. This has led to a massive transfer of people from the thorn countryside to the cities. The people that move to the city are very often poor and have to live in large slum areas, with very poor living conditions as a result [3]. The homes of those living in the slum areas are in most cases not insulated. Bugs and other animals, such as snakes, also causes problems inside houses. The houses are very often made out of poorly joined bricks, which is of great hazard in cases of earthquakes. The brick houses collapses and causes many casualties where people are being buried under, and injured by, falling bricks. Colombian slum areas have a great need for proper housing. Due to the great variations in temperature and weather the homes need to be built in a better insulating material. There is also a need for properly sealed houses where bugs and animals can not enter. The greatest need of all is the one for safer buildings in case of earthquakes [4].

2 Project assignment

The overall assignment is to design a house, regarding dimensions and choice of material. The house should also fulfil needs such as properly insulating material, seal for insects and snakes and most important of all; it should be earthquake proof [4].

2.1 The house

2.1.1 Design

The house should be built with a light sloping roof in order to transport and possibly collect rainwater. In order to let the sunlight and air in, the house should also have window openings. Instead of glass the window openings should be equipped with mosquito nets. To protect from low temperatures and bad weather the window openings should have hatches. These could be made out of the spare pieces that are left when cutting holes for the window openings.

Figure 1: Pictures of a simple model of the house.

The house should consist of two bedrooms, a living room with a kitchen area and a special room for sanitation. The kitchen and sanitation areas could be connected with a rain water tank. See figure 2 for planning of the house.
2.1.2 Construction
The house should be constructed with a sandwich technique, with a core of plastic rigid foam and a fibre reinforced plastic as surface material. The construction should be self carrying, i.e. no extra parts except the walls itself are allowed to support the structure. It will be built on an existing concrete foundation. The construction should be easy to manufacture and assemble. As much as possible of the house production, such as foaming of the rigid plastic foam and making of the surface material, should be able to be done on site. The construction material should be as cheap as possible but still with sufficient mechanical behaviour.

2.2 Location
This project aims to construct a house that should be built and used in the slum areas of Medellin, Colombia. Medellin is located at about 1500 meter above sea level, in the central parts of Colombia.

2.3 Delimitations
Due to the time aspects some issues of the designing process are neglected. Some issues that the project group will consider briefly are:
- Climate effects on the materials
- Assembly techniques of the building elements
All other aspects of the project are left out.
3 Method

3.1 Literature studies and internet
To find the adequate background to this project a literature study has been performed. When searching information on the internet, the primary sources has been consulted when possible.

In order to collect information both scientific and popular/practical texts has been used. Examples of scientific texts are articles from scientific magazines and books with a high grade of theoretical base. Examples of practical and popular texts are books intended for hobby enthusiasts.

3.2 Computer Aided Engineering
The mechanical analyses in this thesis will be done using Computer Aided Engineering, CAE. That means that advanced computer software is used throughout the whole design process. The models are created with the software Pro/ENGINEER. The software application Pro/MECHANICA is used to create mechanical analyses. Pro/MECHANICA is a software that uses the Finite Element Method, FEM.
PART A: DESIGN AND CONSTRUCTION

4 The design of the house

4.1 Design Philosophy
The thought of building a house in alternative materials, such as plastic foam and fiber reinforced plastics, is that it will be a fast and easy way to construct houses for people in slum areas. The idea is that you can bring the building material, foam and surface material, to the construction site in liquid form and then create the entire house on site. To construct a house in these materials also have other advantages. The foam, used as core material, is commonly used as an insulation material in houses. The house will therefore be sufficiently insulated for the cold temperatures that can occur in parts of Colombia. A house built of plastic will also be properly sealed, without cracks and openings for bugs and other animals to enter. The biggest advantage of building a house in these materials, compared to conventional ones, is that it is believed to be much safer in case of seismic activity. The thought is that the house will withstand earthquakes better due to the flexibility of the material. The material is also very light, in comparison to conventional materials. This would, in case of total collapse, reduce the danger of being trapped under or injured by falling parts.

4.2 Dimensions of the house
One of the standard dimensions of plastic rigid foam boards is 2400 x 1200 mm. This standard has been used to set the dimensions of the house. The house is modelled to be 7.2 meters long and 6 meters wide. The height of the building is 2.4 meters on the front side and 2 meters on the backside. The height two meters is set to create an acceptable indoor environment in combination with a sloping roof for transportation of the rain water. The area of the roof is set to be 7 times 8 meters, so that it would reach out from the walls, in order to avoid water from poring down the walls. The roof will be located to create an extended overhang over the front side of the house. This will give some extra protection from water in case of rain. See figure 3 and 4.
4.3 Wall thickness

The wall thickness will be decided by means of FE-analyses described in chapter 9 to 15. The plastic rigid foam boards can be purchased in different standard thickness, for example; 50 mm, 70 mm and 100 mm. The “feeling” of the product, and how it is experienced by the user, and not only the critical values is important [5]. Therefore the core thickness of 50 mm is not tested in this thesis, since this would make the walls too thin and therefore create a feeling of instability of the building. Thicker walls than 100 mm is not expected to be needed. The thickness of the surface material is depending on the number of layers of fibres and matrix that will be used.

5 Sandwich construction

A sandwich construction is made basically of two different materials. There is a lightweight core material that separates two layers of a force bearing skin materials. Sandwich constructions are used in all sorts of applications, from simple objects like doors to much more complex design such as airplane wings. The sandwich technique is an easy way to make a design both light and strong [6]. The principle of sandwich constructions is based
on the fact that the tension in a bended beam is concentrated to the beam surfaces. See Figure 5.

![Figure 5: Schematic sketch of a bended beam. Picture taken from [6].](image)

### 5.1 Skin material

The ability to carry tensile stresses is the most significant feature of the skin material. Examples of materials used as skin materials in a sandwich construction are: plastic composites, sheet metal and wood [6]. According to the project assignment (Chapter 2.1.2) a plastic composite will be used as skin material.

### 5.2 Core

The main objective of the core material is to separate the force bearing material so that the construction becomes stiffer and stronger. There are three main types of core materials:

- Wood
- Honeycomb
- Rigid plastic foam

Balsa is the most frequently used kind of wood in sandwich constructions, due to its relatively light weight. Other sorts of wood with higher density could sometimes be used, but then mostly with the purpose to be load carrying instead of separating the force bearing material.

Honeycomb is not a specific material but a technique. The core is made out of thin plates assembled into a hexagonal shaped structure, see Figure 6. The walls could be made of cardboard, different plastics, metal or composites [6].

![Figure 6: Simple sketch of honeycomb. Picture taken from [6].](image)

Most available rigid plastic foams can be used as a core material. Most plastic rigid foams combine low weight with good mechanical properties. Rigid plastic foams are also relatively isotropic which give the ability to design in various shapes. The foam could
also be foamed directly between the surface materials, so called onsite foaming. Polyurethane is the most commonly used foam when foaming onsite [6]. Rigid plastic foam is the core material stated in the project assignment. It is considered superior due to its good isolation properties and the ability to be created on site.

**6 Plastic Composites**

The skin material of the sandwich construction is stated in the project assignment to be of a plastic composite. There are many definitions of composites available. They have at least two things in common:

1) A composite is man-made and consists of two or more materials.
2) The materials in the composite have typical different properties and could therefore complement each other.

Examples of composites are reinforced concrete and fibre reinforced plastics. The reinforcement of the concrete gives the construction strength when pulled and the concrete itself carries the forces when the construction is compressed. The behaviour of reinforced concrete is a typical composite behaviour.

In fibre composites, the fibres high capacity in tensile stress is used in combination with a material, often called matrix, which binds the structure together and carries the compressive stress [7]. In this case, the matrix will be a polymer.

**6.1 Matrix**

There are two different sorts of plastics, thermosets and thermoplastics. Both thermosets and thermoplastics could be used as matrix in the composite. Both materials show advantages and disadvantages.

Thermoplastics are from the beginning in a solid phase, and melts under heat and pressure. When cooled the plastic goes back to its solid phase. The thermoplastics could be reused and reshaped by heating them again. The manufacturing process is rather safe but requires high cost tools and is only defendable in high volume production. Due to complex manufacturing technique, thermoplastics are not an option in this application.

Thermosets are in a liquid face from the beginning, and then transformed into a hard solid. The transformation reaction is started by adding some sort of initiator or catalyst to the fluid, or by adding energy from either heating or UV-radiation. There are mainly three different thermosets used as matrix in fibre composites: Unsaturated Polyester (PU), Vinyl Ester and Epoxy.

The main purpose of the matrix is to hold the fibres together and carry the compressive stress. It is therefore important that the plastic resin has the ability to “wet” the fibres properly; this means that the resin needs to embed the fibres totally. It is also very important that the resin can keep its form through the hole hardening process [8].
6.2 Fibres

Typical fibres that are used in reinforced plastic composites are: glass fibres, carbon fibres, aramid fibres, fibre made of thermoplastics and a variety of natural fibres. The fibres could appear in different structures such as: flock, woven, mats, and rowing.

Glass fibre is the most commonly used fibre in fibre reinforced plastics. Glass fibres are manufactured in different qualities with various characteristics. E-glass is the most used glass fibre. E-glass combines relatively low price with good mechanical properties. Other existing qualities of glass fibres are: S-glass, R-glass, T-glass, C-glass and some special glass fibres. There is a great variation both in price and mechanical properties between the different sorts. For example C-glass has good resistance against corrosion and other substances that could effect the quality of the final lamina.

Carbon fibres are along with aramid fibres so called high performance fibres. The carbon fibre has generally a higher price than glass fibre, but has also better mechanical characteristics. The carbon fibre has a low ability to be stretched, and breaks rapidly. Aramid fibres are hard to cut and have good ability to handle impacts, and are therefore often used in applications such as helmets, bullet proof west’s and other products for self protection. The fibres stiffness which gives theme a lot of benefits, is also a disadvantage since the material also has low compression strength.

The thermoplastic fibres have often very good mechanical characteristics in combination with low density. Their low melting temperature however makes them unsuitable for many applications.

There are many different types of natural fibres, for example: linen, coconut, banana and hampa. All of the natural fibres have relatively low mechanical characteristics, but also low price. The natural fibres are therefore mostly used in low capacity applications. The nature fibres are more often used as filler in plastics [8].

7 Choice of material

There are four different core materials available on the market for this kind of construction; Rigid Polyvinyl Chloride foam (PVC), Expanded Polystyrene (EPS), Rigid Polyurethane foam (PU) and Polymethylmethacrylate (PMMA) foam. They can be combined with different skin materials depending on the solvent of the skin material. The core materials that can not be dissolved by Styrene can be combined with UP and Vinyl Ester. The core materials that are dissolved by Styrene can only be combined with Epoxy. The Table below show the different combinations available and their advantages and disadvantages [9].
### Table 1: Combinations of available core and skin material [9].

<table>
<thead>
<tr>
<th>Core Material</th>
<th>Compatible Skin Material</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>PVC</td>
<td>UP Vinyl Ester</td>
<td>Good mechanical characteristics.</td>
<td>Bad safety in case of fire, non recyclable.</td>
</tr>
<tr>
<td>EPS</td>
<td>Epoxy</td>
<td>Cheap core material, and good mechanical characteristics.</td>
<td>Expensive Skin Material.</td>
</tr>
<tr>
<td>PU</td>
<td>UP Vinyl Ester</td>
<td>Can be foamed on site. Cheap core material. Cheap skin material.</td>
<td>Poor mechanical characteristics</td>
</tr>
<tr>
<td>PMMA</td>
<td>UP Vinyl Ester</td>
<td>High heat resistance</td>
<td>Expensive core material.</td>
</tr>
</tbody>
</table>

The material combination that best matches the project assignment demands, in respect to price and possibility to on-site foaming, is a combination of Polyurethane foam with a skin of Unsaturated Polyester. The foam is relatively low-cost and has the advantage of being compatible with Unsaturated Polyester, which is the most price worthy of the skin materials. The lesser mechanical properties of the polyurethane foam should not be a problem due to the small amount of stress that occurs in the core material in a sandwich construction. The polyester resin will be reinforced with a 30 percent E-glass fibre mat. This is the cheapest of all fibres and also has the lowest mechanical values of all fibres. However this can easily be compensated for by choosing different skin thicknesses.

The following text handles only the chosen materials.

#### 7.1 Fire safety

Fire safety is essential both during the design of the house and under during the actual building of the house. The matters concerning fire safety during the building of the house will be dealt with in the chapter regarding manufacturing techniques.

The exact behaviour of the chosen materials in case of fire varies between different manufacturers. It is therefore essential to get the accurate information from the material supplier. There are a variety of different gases produced when the rigid foam is burning; some might be irritating and some toxic. The most common gasses produced are carbon dioxide and carbon monoxide. The rigid foam is generally considered to catch fire rather easy, and therefore a need for some sort of material to protect it from exposure of high temperatures and ignition [10]. In this case the fibre reinforced polyester serves as the protection material for the foam. The fibre reinforced polyester has good fire resistant characteristics. There are also fire resistant additives available to mix in the matrix material of the surface [8].
7.2 Climate effect on the material

There are many different factors from the surrounding environment that could effect the final product. Examples of factors are: temperature, chemicals, ultra-violet radiation and humidity. It is important to consult the material supplier to get the exact information regarding the chosen construction. If the manufacturing is done properly the only part that is exposed to the surrounding environment is the skin material. High temperatures could effect the core, but should not be a problem under normal circumstances. Glass fibre reinforced polyester has good chemical characteristics in all areas except for strong bases and strong oxidants. There are different methods available to make the product more resistant to exposure of the environment [8]. The environmental factor, of the area around Medellin, which could effect the polymers, is mainly UV exposure.

8 Manufacturing techniques

8.1 The Polyurethane rigid foam

The polyurethane foam could be bought in blocks ready to use from a retailer or foamed on site. In on-site-foaming, two different chemicals are mixed and a chemical reaction is started. The mixture starts to expand and get rigid. The foaming process is quick, it starts within seconds and take only a couple of minutes to finish. The foam continues to expand even after the foam has got rigid. It is therefore important that the mould is stable and hard enough to handle the pressure [11].

The chemicals used to manufacture the rigid foam could be dangerous if handled in the wrong way. It is important to remember that high pressure could be produced when chemicals are mixed or exposed to high temperatures. High pressure might result in explosions. There is also a risk of self ignition if chemicals are mixed in an improper way. It is therefore highly recommended that persons handling the process is trained and educated for the job. If the foam catches fire, a fine water spray is a good way to fight it [10].

Toxic fumes are produced during the foaming process; which might cause problems for those who deal with the process. Always care for good ventilation when performing this kind of jobs; the process could also be performed outdoors. Even when the process is done outdoors good precaution measures must be uphold. It is, if possible, also advantageous to use a fresh air mask during the procedure [11].

8.2 The composite

By applying the fibres and the thermoset in layers a strong lamina is created. It is essential that the different layers of fibres are applied wet in wet. This means that a new layer is laid before the earlier ones have hardened. This could be complicated when larger areas should be laminated, due to time aspects. When it is impossible to lay the fibre wet
in wet, the surface needs to be treated before a new layer could be applied. Acetone is used to prepare the surface, when polyester is used as resin of the composite.

It is also essential to avoid bubbles of air in the final product, since this could cause weaknesses in the final material. There are different methods to avoid bubbles in the lamina and all of them are performed when the material still is wet. In this case some sort of mechanical variant is preferable where the lamina is “pressed” manually with a roller. If the manufacturing would be performed in larger scale some sort of pressure or vacuum device would be used to remove the air from the material.

Mistakes during the lamina process could be critical to the final construction. If the lamina is made in a bad way, delamination could occur with bad mechanical properties as a result. Delamination is when the different layers of the lamina devide. It is also important that the surface of the rigid foam is treated properly so that the lamina could attach to the foam. The whole construction could collapse totally if the lamina delaminates or if the lamina detaches from the foam. The manufacturers of the different chemicals need to be consulted in order to get proper information, so that the final product gets high quality [6].

8.3 Creation of the sandwich panels

The sandwich panels, created out of the polyurethane foam and the composite, are assembled with hand-lay-up technique. This is the most common technique used by hobby enthusiasts and small industries. In the hand-lay-up process, the fibre mat will be applied directly on the core material. The liquid thermosetting resin will then be applied by hand with help of a roller or a brush. The process will be repeated until the required number of lamina is reached [6].
PART B: FINITE ELEMENT ANALYSIS OF REGULAR LOADS

To determine the thickness of both the core and surface material, a series of FE-analyses is conducted. The model is created in the software ProEngineer and the analyses are performed with ProMechanica.

9 The model

If the geometry of the model can be simplified, without unacceptable loss of accuracy, it is common practice to do so. All geometry that does not provide any essential information for the analysis is also deleted [12]. This is done to make the analysis faster and easier to analyse. This gives a final analysis model with many simplifications. In order to compensate for possible oversimplifications, the contribution from geometry in the Factor of Safety will be raised. See chapter 13 for further information regarding the Factor of Safety.

Figure 7: Model with simplifications explained

When built, the roof will be fixed to the walls with the polyester and glass fibre composite. This will give a very strong and ductile joint. Therefore the walls and roof will be modelled as a solid piece instead of two separate pieces and a joint with plastic behaviour.

The core material in the sandwich construction will be shaped into block elements. In reality these blocks will be joined together by the skin material. In the model, however, they will be described as one solid block. This will not effect the accuracy of the analysis because of the very small amount of stress that is absorbed by the core in a sandwich construction. In Figure 8 an analysis has been done to show the stress in the core. It can be observed that the maximum von Mises stress will not exceed 1 MPa. Details about the analysis are found in Appendix I.
In reality, the model will not have sharp edges in corners because of the manufacturing techniques used. It is also unwise to use sharp edged corners because of the singularities it creates when running the analyses. Therefore a radius has been given to all corners and sharp edges, besides those that will coincide with the concrete plate. In order to avoid too many small elements in the mesh due to the small radius, the radius is modelled slightly larger than the actual radius. This will, however, not effect the result since critical stresses are not found in the corners.

To simplify the analysis and decrease the time and power necessary to make the analysis, the skin material in the sandwich construction is modelled with shells. The shells are fixed completely to the core material of the construction which is not the case in reality. This error is however acceptable because the joint between core and skin material is good and it will also be accounted for in the determination of Factor of Safety. The mesh is automatically generated and divides the model into 12 000 elements, where 3000 are shells and 9000 are solids.
10 Loads

**10.1 Gravity Load**

The house must be able to carry its own weight. The load from the weight of the construction itself is calculated by the program using the geometrical properties and the density of the material.

**10.2 Maintenance Load**

The load from one person that is detaining himself on the roof, for maintenance or other reasons, is estimated to 1000 N spread on a surface of 300 x 300 mm. The location of the maintenance load is determined by an FE-analysis where a load of 10 000 N is spread over the whole area of the roof. The region with maximum deflection is then localised. The load is placed on this region to create a “worst-case-scenario”.

**10.3 Wind load**

The wind load can be calculated in a simple way by using wind speed, geometrical properties of the house and the location of the house. The load is equivalent to a pressure $p_w$, which could be calculated according to Equation (1). All the formulas, tables and figures in this section originates from the Colombian building code, NSR-98 [13], and the tables and figures are available in Appendix II. The pressure is given by,

$$p_w = C_p \cdot q \cdot S_4$$  \hspace{1cm} (1)

- $C_p$ = Coefficient of pressure [ ]
- $q$ = the dynamic wind pressure [kN/m$^2$]
- $S_4$ = the air density coefficient [ ]
The value of $C_p$ varies depending on the geometrical shape of the building. The geometrical properties of the house (found in Chapter 4) give $h < 2b$ in every direction of the house. This gives $C_p = 1.2 \ [13]$. 

The value of $q$ is taken from Table B.6.4-1 [13]. The required input data is the wind speed which could be found in Figure B.6.5.1 [13], and the altitude of the location. Figure B.6.5.1 [13] gives the wind speed in Medellin to 120 km/h. Since Medellin is situated at the altitude of 1500 meters over sea level, this gives $q = 1.99 \text{kN/m}^2$.

The value of $S_4$ varies depending on the altitude according to Table B6.6 [13] Medellin has an altitude of 1500 meters over the sea level which gives $S_4 = 0.83$.

Since all figures in the equations are known, the pressure $p_w$ could be calculated using Equation (1). The result is $p_w \approx 2 \text{kN/m}^2$.

This formula is a simple way to calculate the wind load. If the wind load is of high significance for the construction a more sophisticated variant is needed. The wind load is in this case however so small that the easier variant could be used.

In ProMechanica it is easier to work with loads consisting of forces than pressure. Therefore the wind load calculated earlier is transformed into a spread force $F_w$ as follows:

$$F_w = A \times p_w \quad (2)$$

where $A$ is the area of the side of the house. This will give four different wind load cases, each corresponding to a side of the house where the wind is working.

11 Constraints

To perform an analysis in Pro/MECHANICA the model needs to be constrained in every direction. The constraints are chosen to resemble the reality as close as possible. While the house will be fixed to a concrete plate the lower surface of the model is fixed in all directions in both translation and rotation. See Figure 10.
12 Material Properties

The material data has been extracted from different sources. Here follows a list of the values used in the analyses.

<table>
<thead>
<tr>
<th>Property</th>
<th>Material</th>
<th>Glass fiber reinforced polyester</th>
<th>Polyurethane foam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density [g/cm$^3$]</td>
<td></td>
<td>1.5 [14]</td>
<td>0.34 [15]</td>
</tr>
<tr>
<td>Poisson’s ratio [$\nu$]</td>
<td></td>
<td>0.3 [see Chapter 12.1]</td>
<td>0.44 [15]</td>
</tr>
<tr>
<td>Compressive strength [MPa]</td>
<td></td>
<td>100 [16]</td>
<td>69 [17]</td>
</tr>
<tr>
<td>Tensile strength [MPa]</td>
<td></td>
<td>120 [14]</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Material properties

The listed values are to be seen as approximations and not definite values. This will not effect the outcome of the analyses because of the high safety factor and relatively low stress and displacement in comparison to the strengths of the materials. There are no values available on tensile strength of the polyurethane foam. This is not a problem because the principle of the sandwich construction is that the skin material will carry most of the stress (See Chapter 15).

12.1 Poisson’s ratio

Poisson’s ratio, $\nu$, is a measure of the tendency of a material to, when stretched out in one direction, get slimmer in the other two directions.
For polymers $\nu$, which is dimensionless, is usually between 0.3 and 0.45. The lower limit is true for hard polymers, short time of load and low temperatures. The upper limit is true for soft polymers, long time of load and high temperatures [19]. Poisson’s ration for the core material is $\nu = 0.44$ [15]. Due to the fact that values for Poisson’s ratio in reinforced polymers is hard to come by and also is variable to the rate of deformation [20], a simple set of FE-analyses was done to determine the ratio’s effect for the shell. This was done with a spread load on the roof and with a Single Pass analysis with a plotgrid value of 4. Poisson’s ratio in the shell was varied between 0 and 0.45 in four steps. This was considered sufficient to show a tendency. The variation in maximum von Mises stress and maximum displacement was studied. The results are shown in Figure 11.

![The effect of Poisson's ratio](image_url)

Figure 11: The effect of Poisson’s ratio on stress and displacement

The conclusion is that the variation of the stress and displacement due to Poisson’s ratio is negligible. Therefore Poisson’s ratio is set to 0.3.

### 13 Factor of Safety

In mechanical engineering it is wise not to dimension against the critical values of the design. Therefore, a safety factor will be introduced in the calculations. There are three ways to work with the safety factor.

1. The force is increased with the safety factor and then used as usual in the calculations. The results could then be compared with the critical variables.
2. The critical values for deflection, stress etc. is decreased with the safety factor. The calculations are followed through as normal and then compared with the decreased critical values.

3. The actual stress is divided with the maximum allowed stress, the quotient is then compared with the safety factor. It is crucial to use the highest appearing stress.

The three definitions are equally correct, but in FE-analysis the third option is preferable due to the fact that the quota can be shown graphically as do the stress [12]. All three techniques are still based on the same formula [21]:

\[ FS = \frac{S_{al}}{\sigma_{ap}} \]  \hspace{1cm} (3)

Where \( S_{al} \) is the allowable strength and \( \sigma_{ap} \) is the applied stress.

The Factor of Safety can be estimated as a combination of the uncertainties of the values of material, stress and geometry as well as the uncertainties in the failure theory and the need for reliability of the construction. One formula to calculate this is [21]:

\[ FS = FS_{material} \cdot FS_{stress} \cdot FS_{geometry} \cdot FS_{failure\_theory} \cdot FS_{reliability} \]  \hspace{1cm} (4)

The contribution from each part of the safety factor is estimated according to the list in Appendix III.

Since the material properties are not well known \( FS_{material} \) is set to 1.3. The loads are well defined and the stress analysis gives fairly accurate results, therefore, \( FS_{stress} \) is set to 1.3. Since the manufacturing technique is a little bit uncertain and the measures probably will varie quit a lot, \( FS_{geometry} \) is set to 1.2. \( FS_{failure\_theory} \) is set to 1.2. \( FS_{reliability} \) is set to 1.3 due to the quite high need of reliability. According to this, Equation (4) gives a factor of safety equal to 3.5.

### 14 Analyses

The analyses are made as Multi Pass Adaptive analyses with a convergence set of 10%. The polynomial order was set to vary from 1 to 9. The mesh was automatically generated in Pro/MECHANICA and is considered sufficient. For maximum von Mises stress the convergence attained is 0.3% and of 12 000 15 elements do not converge. The convergence attained for maximal displacement is 0.2% and of 12 000 elements did 5 converge.

### 15 Test results

Several analyses have been done and the thickness of the core material, the thickness of the surface material and the direction of the wind load has been varied. The tested thicknesses of the core are 100 mm and 70 mm, which are standard sizes available for purchase. The thickness of the surface material has been varied between 7 mm and 2 mm. In manufacturing, every layer of polyester and glass fibre represents 1 mm.
The aim of the tests was to find the combination with least material consumption, and therefore with the lowest cost, that fulfils the requirements. The analysis showed that the test with a 70 mm foam and 2 mm of surface material is enough. The stress found in the core is lower than 0.5 MPa. See Figure 12.

Figure 12: Maximum stress in the core.

The highest stress occurs when the wind load is applied in negative x-direction. See Figure 13 for coordinate system. The largest displacement occurs when the wind load is applied in positive x-direction or negative y-direction. See Figure 14 for coordinate system. This verifies the assumption that the surface material will carry most part of the stress. The maximum von Mises stress and maximum displacement for the different wind load combinations are showed in Table 3.
Table 3: Test results, different wind loads.

<table>
<thead>
<tr>
<th>Wind direction</th>
<th>Max von Mises [MPa]</th>
<th>Max displacement [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>-x</td>
<td>5.8</td>
<td>5.0</td>
</tr>
<tr>
<td>y</td>
<td>5.5</td>
<td>5.2</td>
</tr>
<tr>
<td>-y</td>
<td>3.6</td>
<td>6.3</td>
</tr>
<tr>
<td>x</td>
<td>4.9</td>
<td>6.3</td>
</tr>
</tbody>
</table>

The analyses show that the wind forces counteracts with the maintenance load. An extra analysis with only the maintenance load has therefore been carried out. This analysis resulted in a maximum stress of 3 MPa and a maximum displacement of 6.3 mm. This gives that the maximum occurring stress according to the analyses is 5.8 MPa and the maximum occurring displacement is 6.3 mm.

The location of the stress is shown in Figure 13 and the location of the displacement is shown in Figure 14. The model is shown in deformed state with a scaling of 1611%.

Figure 13: Picture of load combination with maximum stress.
Figure 14: Picture of load combinations with maximum displacement.
PART C: FINITE ELEMENT ANALYSIS FOR EARTHQUAKE DESIGN

16 Earthquake design

In the project assignment it is specified that the house should be earthquake safe. The organisation Ankarstiftelsen believe that the special material used would make the house resistant to earthquakes due to its flexibility.

There are several ways to conduct a seismic analysis of a structure. In this thesis we have used the Colombian building code, NSR -98, to calculate values of the seismic forces that arise due to the ground motion of an earthquake. Those forces have then been applied, in different load combinations, to the house in static analyses using the software ProMechanica. The model and materials that has been used in this analysis is the same as in the analyses performed in previous chapters. The thickness of the core is set to 70 mm and the skin thickness is 2 mm. Constrains used in this analysis is the same as used in previous chapters. No other loads except for gravity loads and the earthquake loads are used in this part.

Most building codes, like the one used here, states that their purpose is to provide for life safety rather than fully prevent damage. This means that a building that is designed in conformance with the building code should be able to: a) resist minor level of earthquake ground motion without damage; b) resist moderate level of earthquake ground motion without structural damage, but perhaps with minor non structural damage and c) resist a major level of earthquake ground motion without a total collapse, but possibly with some non structural and structural damage [22].

The implementation of a seismic analysis can be divided into six steps. The first three handles the 1) creation of the Elastic Acceleration Spectrum Diagram; 2) The calculation of the seismic forces and; 3) the calculation of the accidental torsion. These are the parameters used to create the simulations. The fourth step handles 4) the creation of load combinations, LC. The two last steps handle the verification of the structures earthquake resistance. 5) Calculation of drift and; 6) verification of occurred stress.

All maps and tables from NSR -98 used in the following chapter are attached in Appendix IV.
16.1 Step 1 – The Elastic Acceleration Spectrum Diagram

The Elastic Acceleration Spectrum Diagram, as seen in Figure 15, is the expected acceleration of the soil, $S_a$, depending on the vibration period for the building, $T$. $S_a$ is defined as the maximum acceleration, horizontal to the building, expressed in g. Where $g$ is the gravitational acceleration, 9.8 m/s$^2$ [13]. The diagram differs depending on specific site characteristics. The diagram is used to calculate the seismic forces and the seismic shear. To create the diagram there are certain parameters that needs to be determined; the Seismic risk level, the soil characteristics and the importance factor.

16.1.1 Seismic risk level and $A_a$ value

In NSR -98 the seismic risk is divided into three risk levels; high risk, intermediate risk and low risk. These maps are developed after studying earlier recordings of seismic activity in the area [23]. The risk level also corresponds to a seismic risk value, $A_a$ value. This is a coefficient that represents the peak acceleration of the spot.

By studying map A.2-1 and A.2-2 [13] the seismic risk level in Medellin is determined to intermediate and the $A_a$ value is determined to 0.20.

16.1.2 Soil characteristics, S

The characteristics of the underlying soil are important because of its capacity of transporting the vibrations from the seismic activity. The soil characteristics are determined by a geological research. If no geological research has been done, an estimated value can be used. In this thesis it is not possible to conduct such a research on the site of the building. Therefore, the estimated value $S = S_j = 1.5$ will be used [13].
16.1.3 Importance factor, \( I \)

The importance factor has a scale from I to IV and describes the buildings importance to the community. Hospitals and fire stations, for example, has the importance factor IV while normal houses that is not of essential need to the community has the importance factor I. The building in this thesis is a regular one-family house and therefore has the importance factor I. Each factor corresponds to an importance factor value. The house will have the value \( I = 1.0 \) [13].

16.1.4 The creation of the elastic acceleration spectrum diagram

The elastic acceleration spectrum diagram is given by the following equations. The NSR-98 is using a critical damping of 5%. The acceleration is given by [13],

\[
S_r = \frac{1.2 S I}{T} = \frac{0.36}{T} \quad (5)
\]

When the period is less than \( T_c \), which represents short vibration periods, the acceleration is limited to:

\[
T_c = 0.48 S = 0.72 \quad (6)
\]

\[
S_r = 2.5 A_u I = 0.5g \quad (7)
\]

For periods longer than \( T_L \), which represents long vibration periods, the acceleration is limited to:

\[
T_L = 2.4 S = 3.6 \quad (8)
\]

\[
S_r = \frac{A_u I}{2} = 0.10g \quad (9)
\]

While the dotted line in Figure 15 only applies to dynamic analyses, there is no need to determine \( T_0 \).
16.2 Step 2 – The seismic forces

16.2.1 The seismic shear

The earthquake ground motion creates a seismic shear force, $V_s$. The shear force is equal to the design seismic forces acting on the building's different floors.

![Image of seismic shear](image)

Figure 16: Seismic shear [13].

The seismic shear is given by the equation [13]:

$$V_s = S_a \cdot g \cdot M$$  \hspace{1cm} (10)

Where $S_a$ is the maximum acceleration, expressed as part of the gravitational acceleration, at the building's fundamental period and $g$ is the gravity, $9.8 \, \text{m/s}^2$ [13] and $M$ is the total weight of the building, in this case $4200 \, \text{kg}$ (see Appendix V).

To determine the fundamental period a modal computer analysis is performed (data about the analysis is found in Appendix VI). The first period of the building is found to be 0.1 s. This is defined as the longest period. The modes that create the worst-case scenario therefore have a shorter vibration period than 0.1 s. While the period, $T$, is used only to choose the equation for determination of $S_a$, all values of $T$ below 0.1 s will give the same equation, the modes are not investigated further. The value is chosen to $T = 0.1$ s.

In order to be applicable to the NSR-98 the period found in the computer analysis must be less than $1.2T_a$[13]. Where $T_a$ is the empirical value determined using Rayleigh’s formula [13]:

$$T_a = C_i \cdot h_i^{\frac{3}{2}}$$  \hspace{1cm} (11)

Where $T_a$ is the building's fundamental period, $C_i$ is determined due to building materials and structure configuration and $h_i$ is the height of the building.
While the materials and structural configuration of the house in the present study isn’t listed a value is chosen that apply to all other types of earthquake resistant systems. That gives a value of $C_i = 0.05$ [13].

The height of the building is 2.4 meters. That gives $h_t = 2.4$.

Equation (11) then gives $T_a = 0.1$.

The empirical value, $T_a$, is almost equal to the value found in the modal computer analysis. Therefore, the value $T = 0.1 \text{ s}$ is used in the following calculations.

$S_a$ is determined from the elastic acceleration spectrum diagram by the vibration period equal to $T$. While $T < T_c$, $S_a$ is determined by Equation (7) to be $S_a = 0.5g$.

The seismic shear is then given by Equation (10). $V_s = 20.6kN$.

16.2.2 The seismic force
The seismic force, distributed over the floors of the building as seen in Figure 16, is equal to the seismic shear. While the considered building only has one floor the seismic force will be $F_{seism} = V_s = 20580N \approx 20.6kN$.

16.3 Step 3 – Accidental torsion
Accidental torsion caused by uncertainties in mass and stiffness distribution must be considered. The accidental torsion is equivalent to moving the centre of mass by 5% of the dimensions of the structure [13].

![Figure 17: Accidental torsion [13]](image)

16.3.1 Calculation of the accidental torsion
The torsional moments acting on the structure when the seismic force is acting in the $x$ respectively $y$ directions are given by:
\[ M_x = 0.05 \ F_{seism} \ L_x \approx 7.4kNm \] 
\[ M_y = 0.05 \ F_{seism} \ L_y \approx 6.2kNm \] 

For definition of \( L_x \) and \( L_y \) see Figure 3.

### 16.4 Step 4 – Load combinations

The seismic analyses are composed by the seismic force and torsional moments in different load combinations, \( LC \). While the forces can act on the structure in eight directions, there will be eight load combinations. In order to account for irregularities in the building, the NSR -98 demands an additional force, acting perpendicular, in the horizontal plane, to the considered direction of the seismic force. This force shall be 30\% of the seismic force [13].

This creates the following load combinations:

\[
\begin{align*}
F_{seism}X + 0.3 \ F_{seism}Y + M_x & \quad \text{LC 1} \\
F_{seism}X - 0.3 \ F_{seism}Y + M_x & \quad \text{LC 2} \\
- F_{seism}X + 0.3 \ F_{seism}Y + M_x & \quad \text{LC 3} \\
- F_{seism}X - 0.3 \ F_{seism}Y + M_x & \quad \text{LC 4} \\
F_{seism}Y + 0.3 \ F_{seism}X + M_y & \quad \text{LC 5} \\
F_{seism}Y - 0.3 \ F_{seism}X + M_y & \quad \text{LC 6} \\
- F_{seism}Y + 0.3 \ F_{seism}X + M_y & \quad \text{LC 7} \\
- F_{seism}Y - 0.3 \ F_{seism}X + M_y & \quad \text{LC 8}
\end{align*}
\]

The seismic forces are applied at created surface regions at the top of the walls and the moment is applied at the roof. This is shown in Figure 18.
The analyses are made in the software Pro/MECHANICA as multi pass static analyses with a polynomial order of 9 and a convergence of 10%. The attained convergence of the analyses is showed in Appendix VII.

16.5 Step 5 - Horizontal displacement and drift

The drift, $\Delta$, is defined as the relative horizontal displacement between two points placed in a vertical line [13].
Therefore the corners upper and lower points are chosen for the comparison. The corners are named A, B, C and D.

![Diagram of corners A-D](image)

**Figure 20:** Definitions of corners A-D.

The displacements in $x$ and $y$ directions are presented in the table below.

<table>
<thead>
<tr>
<th>Displacement [µm]</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LC</strong></td>
<td>x</td>
<td>y</td>
<td>x</td>
<td>y</td>
</tr>
<tr>
<td>1</td>
<td>200</td>
<td>64</td>
<td>120</td>
<td>53</td>
</tr>
<tr>
<td>2</td>
<td>180</td>
<td>-12</td>
<td>130</td>
<td>-41</td>
</tr>
<tr>
<td>3</td>
<td>-110</td>
<td>27</td>
<td>-190</td>
<td>100</td>
</tr>
<tr>
<td>4</td>
<td>-110</td>
<td>-59</td>
<td>-180</td>
<td>2.6</td>
</tr>
<tr>
<td>5</td>
<td>84</td>
<td>180</td>
<td>23</td>
<td>200</td>
</tr>
<tr>
<td>6</td>
<td>-14</td>
<td>170</td>
<td>-64</td>
<td>220</td>
</tr>
<tr>
<td>7</td>
<td>47</td>
<td>-120</td>
<td>67</td>
<td>-110</td>
</tr>
<tr>
<td>8</td>
<td>-43</td>
<td>-120</td>
<td>-26</td>
<td>-100</td>
</tr>
</tbody>
</table>

**Table 4:** Displacement.

The drift is calculated from the displacements in the $x$ and $y$ directions respectively using the Pythagorean Theorem.

<table>
<thead>
<tr>
<th>Drift [µm]</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LC</strong></td>
<td>A</td>
<td>B</td>
<td>C</td>
<td>D</td>
</tr>
<tr>
<td>1</td>
<td>210</td>
<td>131</td>
<td>120</td>
<td>103</td>
</tr>
<tr>
<td>2</td>
<td>180</td>
<td>136</td>
<td>172</td>
<td>68</td>
</tr>
<tr>
<td>3</td>
<td>113</td>
<td>215</td>
<td>118</td>
<td>161</td>
</tr>
<tr>
<td>4</td>
<td>125</td>
<td>180</td>
<td>101</td>
<td>184</td>
</tr>
<tr>
<td>5</td>
<td>199</td>
<td>201</td>
<td>86</td>
<td>136</td>
</tr>
<tr>
<td>6</td>
<td>171</td>
<td><strong>229</strong></td>
<td>119</td>
<td>125</td>
</tr>
<tr>
<td>7</td>
<td>129</td>
<td>129</td>
<td>181</td>
<td>130</td>
</tr>
</tbody>
</table>
Table 5: Calculated drifts.

The maximum drift may not exceed 1% of the height of the building [13]. This gives a maximum allowed drift of $\Delta_{\text{max}} = 24 \text{ mm}$.

The largest drift value is found in corner B with LC 6. It measures $229 \mu\text{m}$ which is well under the limit of 24mm.

### 16.6 Step 6 - Stress caused by the seismic forces

The stresses created by the seismic forces are well below the allowed values as showed in the table below.

<table>
<thead>
<tr>
<th>LC</th>
<th>Maximum von Mises stress [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.1</td>
</tr>
<tr>
<td>2</td>
<td>3.1</td>
</tr>
<tr>
<td>3</td>
<td>3.4</td>
</tr>
<tr>
<td>4</td>
<td>3.3</td>
</tr>
<tr>
<td>5</td>
<td>1.9</td>
</tr>
<tr>
<td>6</td>
<td>2.3</td>
</tr>
<tr>
<td>7</td>
<td>1.2</td>
</tr>
<tr>
<td>8</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Table 6: Maximum von Mises stress.

The location of the maximum von Mises stress in LC 3 is shown in figure 21. The model is showed in deformed state with a scaling of 2605 %. 
Figure 21: Location of maximum von Mises stress in LC 3.
Conclusions

The chosen materials, Polyurethane foam and E-glass fibre reinforced polyester, is in conformance with the Project assignment (Chapter 2). The polyurethane foam will provide good insulation and good stability while the reinforced polyester will give a good protection for the core material and will also seal the house. The materials that are used could easy be manufactured on site, in the meaning that the different techniques are available and used by hobby enthusiasts.

The manufacturing processes involved are however rather complex, therefore, training and exercise in the craft of plastic making is essential. We believe that a person with basic technical knowledge and with a bit of practice could build the house without problem. The family that is going to occupy the house could also be involved in the building process. We believe that this is important because of the feeling of participation that it creates.

The Finite Element Analysis of the regular loads shows that the stresses in the materials are far from the critical values when gravity, maintenance and wind loads are applied. The maximum allowed stress in the glass fibre is about 100 MPa, as seen in Table 2. The FEM-analysis, with a surface thickness of 2 mm and core thickness of 70 mm, gives a value of maximum stress of 5.8 MPa with regular loads. The Factor of Safety is chosen to 3.5 in Chapter 13. The maximum occurring stress, with safety factor considered, is 20.3 MPa which is much less then the allowed 100 MPa.

As mentioned in Chapter 4.3 not only the critical values are important when designing. It is also equally important how the product is felt by the user. It won’t “feel” safe if parts of the house are moving too much under regular loads. Therefore, we have chosen the displacement as a dimensional criterion when designing the house. We have chosen a maximum displacement of 30 mm in order for the house to still “feel” safe. With the safety factor considered, the maximum allowed displacement will be 8.6 mm. The analysis with 2 mm surface thickness gives a displacement of 6.3 mm, which lies within the limit.

Even though the displacement probably would be within limits also with a surface thickness of only 1 mm, the recommended thickness of the skin material is 2 mm. This represents two layers of fibres in the lamina. This recommendation is made due to uncertainties in the manufacturing techniques. Examples of critical parameters during the manufacturing process are: the wetability of the fibres, delamination, the connection between core and skin and the quality of the onsite foamed polyurethane. With two layers of lamina, the risk of critical parameters in manufacturing causing weak spots in the surface is minimized, exception: delamination. The problem with delamination is very hard to solve by theoretical reasoning and must be evaluated by empirical studies. This is not considered at all in this thesis.

The Finite Element Analysis of the Earthquake loads shows that the maximum drift of 0.229 mm. This is far below the maximum allowed drift of 24 mm. The stresses caused
by the seismic forces are also far below the maximum allowed values. The largest stress is found to be 3.4 MPa (see Table 6) while the maximum allowed stress in the glass fibre is 100 MPa and 69 MPa in the polyurethane foam (Table 2). The Colombian building code has some limitations and does not struggle to totally prevent damage, but to provide life safety. Despite this we believe that, based on the indication of low stresses, the house will probably stand through a major level of earthquake ground motion without structural damage.

17 Recommendations for further development and advice for implementation

While working with this project we have considered further developments of the main idea. Due to time aspects we have not had the possibility to develop them further. In the end of this chapter we also give some advice for the realization of the project.

The roof of the house could be used as a collector for rainwater if it is equipped with a gutter, drainpipe and a water tank. The water tank could be placed on the backside of the house and then connected with piping to the kitchen and sanitation areas. It could also be a good idea to extend the roof over a porch on the side of the house; which could serve as an extra social area, which is quite common in South America.

The concept of an onsite manufactured simple house could also be applied in emergency relief situations. Areas who are exposed to earthquakes in poor countries often take long time to rebuild, and as a consequence people live in temporary tent villages for a long time. This concept could give them proper houses quite easy and fast.

We believe that the easiest way to manufacture the house is to start by creating the sandwich panels with the outer dimensions of the walls and the roof. Big panels with few joints are preferable in order to achieve good mechanical properties. The holes that are needed for doors and windows are then cut out, before assembling the house. The panels are attached to each other by using the same materials as in the lamina to glue the parts together. To reinforce the joints an extra layer of fibre is applied on both the inside and the outside of the corners. The material that is cut out for the door- and the window openings could then be used to make doors and window hatches.

There are several issues needed to be handled before the building project could be started. An investigation about exact availability and prices of the materials needs to be performed. When this is investigated tests with the chosen materials are needed to be done. New analyses needs to be conducted if the mechanical characteristics differ much from values obtained in this thesis. It is also essential that the person that is in charge of the building process has done some test lamination and foaming, so that he or she is familiar with the process.
References


APPENDIX I – Analysis of the stress in the core

The analysis made is a Single Pass Adaptive. With a plotting grid of 4. The load is 10 000 N applied over the roof. The stress error is showed in the picture below.

<table>
<thead>
<tr>
<th>Load Set</th>
<th>Stress Error</th>
<th>% of Max Prin Str</th>
</tr>
</thead>
<tbody>
<tr>
<td>LoadSet1</td>
<td>7.63e-02</td>
<td>0.4% of 1.93e+01</td>
</tr>
</tbody>
</table>
APPENDIX II - Tables and figures used for wind load calculations

**Tabla B.6.4-1 - Valores de \( q \) en kN/m\(^2\) (1 kN/m\(^2\) = 100 kgf/m\(^2\))**

<table>
<thead>
<tr>
<th>Altura (m)</th>
<th>60</th>
<th>70</th>
<th>80</th>
<th>90</th>
<th>100</th>
<th>110</th>
<th>120</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 10</td>
<td>0.20</td>
<td>0.27</td>
<td>0.35</td>
<td>0.45</td>
<td>0.55</td>
<td>0.67</td>
<td>0.79</td>
</tr>
<tr>
<td>10 - 20</td>
<td>0.22</td>
<td>0.30</td>
<td>0.40</td>
<td>0.50</td>
<td>0.62</td>
<td>0.75</td>
<td>0.89</td>
</tr>
<tr>
<td>20 - 40</td>
<td>0.27</td>
<td>0.37</td>
<td>0.48</td>
<td>0.61</td>
<td>0.75</td>
<td>0.91</td>
<td>1.08</td>
</tr>
<tr>
<td>40 - 80</td>
<td>0.33</td>
<td>0.45</td>
<td>0.59</td>
<td>0.74</td>
<td>0.92</td>
<td>1.11</td>
<td>1.32</td>
</tr>
<tr>
<td>80 - 150</td>
<td>0.40</td>
<td>0.54</td>
<td>0.71</td>
<td>0.90</td>
<td>1.11</td>
<td>1.34</td>
<td>1.59</td>
</tr>
<tr>
<td>&gt; 150</td>
<td>0.50</td>
<td>0.68</td>
<td>0.88</td>
<td>1.12</td>
<td>1.38</td>
<td>1.67</td>
<td>1.99</td>
</tr>
</tbody>
</table>

(*véase la figura B.6.5-1*)

**Tabla B.6.4-2 - Valores de \( C_n \) para superficies verticales**

<table>
<thead>
<tr>
<th></th>
<th>1.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estructuras prismáticas con ( h &lt; 2b )</td>
<td></td>
</tr>
<tr>
<td>Estructuras prismáticas alargadas</td>
<td>1.6</td>
</tr>
<tr>
<td>Superficies cilíndricas</td>
<td>0.7</td>
</tr>
<tr>
<td>Superficies planas de poca profundidad tales como vallas</td>
<td>1.4</td>
</tr>
</tbody>
</table>

**Tabla B.6.6 - Coeficiente \( S_4 \)**

<table>
<thead>
<tr>
<th>Altitud (m)</th>
<th>( S_4 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.00</td>
</tr>
<tr>
<td>500</td>
<td>0.94</td>
</tr>
<tr>
<td>1000</td>
<td>0.88</td>
</tr>
<tr>
<td>1500</td>
<td>0.83</td>
</tr>
<tr>
<td>2000</td>
<td>0.78</td>
</tr>
<tr>
<td>2500</td>
<td>0.73</td>
</tr>
<tr>
<td>3000</td>
<td>0.69</td>
</tr>
</tbody>
</table>
Nota: Estas zonas no han sido estudiadas y se recomienda ser conservador al evaluar las fuerzas eólicas que puedan presentarse en ellas. Mientras no existan datos confiables se calcularán con base en una velocidad mínima de 100 km/h.

Mapa de amenaza eólica: velocidad del viento básico
Figura B.6.5.1
APPENDIX III – Factor of Safety

Estimating the contribution for the material

\[ FS_{\text{material}} = 1.0 \]

If the properties of the material are well known and if they have been experimentally obtained from tests on a specimen known to be identical to the component being designed and from tests representing the loading to be applied.

\[ FS_{\text{material}} = 1.1 \]

If the material properties are known from a handbook or are given by the manufacturer.

\[ FS_{\text{material}} = 1.3 - 1.4 \]

If the material properties are not well known.

Estimating the contribution for the load stress

\[ FS_{\text{stress}} = 1.0 - 1.1 \]

If the load is well defined as static or fluctuating, if there are no anticipated overloads or shock loads, and if an accurate method of analyzing the stress has been used.

\[ FS_{\text{stress}} = 1.2 - 1.3 \]

If the nature of the load is defined in an average manner, with overloads of 20-50 percent, and the stress analysis method may result in errors less than 50 percent.

\[ FS_{\text{stress}} = 1.4 - 1.7 \]

If the load is not well known or the stress analysis method is of doubtful accuracy.

Estimating the contribution for geometry (unit-to-unit)

\[ FS_{\text{geometry}} = 1.0 \]

If the manufacturing tolerances are tight and held well.

\[ FS_{\text{geometry}} = 1.0 \]

If the manufacturing tolerances are average.

\[ FS_{\text{geometry}} = 1.1 - 1.2 \]

If the dimensions are not closely held.

Estimating the contribution for failure analysis

\[ FS_{\text{failure theory}} = 1.0 - 1.1 \]

If the failure analysis to be used is derived for the state of stress, as for uniaxial or multiaxial static stresses, or fully reversed uniaxial fatigue stresses.

\[ FS_{\text{failure theory}} = 1.2 \]

If the failure analysis to be used is a simple extension of the above theories, such as for multiaxial, fully reversed fatigue stresses or uniaxial nonzero mean fatigue stresses.

\[ FS_{\text{failure theory}} = 1.3 - 1.5 \]

If the failure analysis is not well developed, as with cumulative damage or multiaxial nonzero mean fatigue stresses.

Estimating the contribution for reliability

\[ FS_{\text{reliability}} = 1.1 \]

If the reliability for the part need not be high, for instance, less than 90 percent.

\[ FS_{\text{reliability}} = 1.2 - 1.3 \]

If the reliability is an average of 92-98 percent.
If the reliability must be high, say, greater than 99 percent.

[20]
APPENDIX IV - Tables and figures used for earthquake load calculations

[Map A.2-1]
Mapa de Valores de $\lambda_a$

Figura A.2-2
### TABLA A.2-3
**VALORES DEL COEFICIENTE DE SITIO, S**

<table>
<thead>
<tr>
<th>Tipo de Perfil de Suelo</th>
<th>Coeficiente de Sito, S</th>
</tr>
</thead>
<tbody>
<tr>
<td>S₁</td>
<td>1.0</td>
</tr>
<tr>
<td>S₂</td>
<td>1.2</td>
</tr>
<tr>
<td>S₃</td>
<td>1.5</td>
</tr>
<tr>
<td>S₄</td>
<td>2.0</td>
</tr>
</tbody>
</table>

[Table A.2-3]

### TABLA A.2-4
**VALORES DEL COEFICIENTE DE IMPORTANCIA, I**

<table>
<thead>
<tr>
<th>Grupo de Uso</th>
<th>Coeficiente de Importancia, I</th>
</tr>
</thead>
<tbody>
<tr>
<td>IV</td>
<td>1.3</td>
</tr>
<tr>
<td>III</td>
<td>1.2</td>
</tr>
<tr>
<td>II</td>
<td>1.1</td>
</tr>
<tr>
<td>I</td>
<td>1.0</td>
</tr>
</tbody>
</table>

[Table A.2-4]

\[ C_t = 0.08 \] para pórticos resistentes a momentos de concreto reforzado y para pórticos de acero estructural con diagonales excéntricas

\[ C_t = 0.09 \] para pórticos resistentes a momentos de acero estructural.

\[ C_t = 0.05 \] para los otros tipos de sistema de resistencia sísmica.

[A.4.2.2]
APPENDIX V - Calculations of the mass of the house

\[ \rho_{\text{surface}} = 1500 \text{kg/m}^3 \]
\[ \rho_{\text{core}} = 340 \text{kg/m}^3 \]

\[ V_{\text{surface}} = (2.20(2 \cdot 7.20 + 2 \cdot 6 + 0.12) \cdot 2 + 2 \cdot 7 \cdot 8) \cdot 0.002 = 0.56192 \text{m}^3 \]
\[ V_{\text{core}} = (2.20(2 \cdot 7.20 + 2 \cdot 6 + 0.12) + 7 \cdot 8) \cdot 0.07 = 9.8336 \text{m}^3 \]

\[ M = \rho_{\text{surface}} \cdot V_{\text{surface}} + \rho_{\text{core}} \cdot V_{\text{core}} \approx 4200 \text{kg} \]
APPENDIX VI – Modal analysis

The analysis is made as a Multi Pass Adaptive analysis with a convergence set of 10%. The polynomial order is set to vary from 1 to 9. The convergence attained is seen to be between 2.1% and 6.6%.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency (Hz)</th>
<th>Convergence</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.083187e+01</td>
<td>2.1%</td>
</tr>
<tr>
<td>2</td>
<td>1.809023e+01</td>
<td>3.1%</td>
</tr>
<tr>
<td>3</td>
<td>1.876963e+01</td>
<td>3.1%</td>
</tr>
<tr>
<td>4</td>
<td>2.017397e+01</td>
<td>2.7%</td>
</tr>
<tr>
<td>5</td>
<td>2.072934e+01</td>
<td>3.4%</td>
</tr>
<tr>
<td>6</td>
<td>2.281527e+01</td>
<td>4.8%</td>
</tr>
<tr>
<td>7</td>
<td>2.479975e+01</td>
<td>4.4%</td>
</tr>
<tr>
<td>8</td>
<td>2.525182e+01</td>
<td>4.9%</td>
</tr>
<tr>
<td>9</td>
<td>2.658515e+01</td>
<td>6.3%</td>
</tr>
<tr>
<td>10</td>
<td>2.754281e+01</td>
<td>6.6%</td>
</tr>
<tr>
<td>11</td>
<td>2.843725e+01</td>
<td>5.9%</td>
</tr>
<tr>
<td>12</td>
<td>2.996959e+01</td>
<td>5.6%</td>
</tr>
<tr>
<td>13</td>
<td>3.046706e+01</td>
<td>4.0%</td>
</tr>
<tr>
<td>14</td>
<td>3.075062e+01</td>
<td>6.2%</td>
</tr>
<tr>
<td>15</td>
<td>3.103211e+01</td>
<td>6.0%</td>
</tr>
<tr>
<td>16</td>
<td>3.190212e+01</td>
<td>5.6%</td>
</tr>
<tr>
<td>17</td>
<td>3.308393e+01</td>
<td>6.1%</td>
</tr>
<tr>
<td>18</td>
<td>3.356498e+01</td>
<td>6.2%</td>
</tr>
<tr>
<td>19</td>
<td>3.395519e+01</td>
<td>6.6%</td>
</tr>
<tr>
<td>20</td>
<td>3.505117e+01</td>
<td>4.9%</td>
</tr>
</tbody>
</table>

The frequencies of the modes and the convergence.
### Appendix VII – Convergence of Earthquake Analyses

<table>
<thead>
<tr>
<th>LC</th>
<th>Displacement x</th>
<th>Displacement y</th>
<th>Max von Mises stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.3</td>
<td>0.1</td>
<td>0.5</td>
</tr>
<tr>
<td>2</td>
<td>0.4</td>
<td>0.1</td>
<td>0.4</td>
</tr>
<tr>
<td>3</td>
<td>0.2</td>
<td>0</td>
<td>0.3</td>
</tr>
<tr>
<td>4</td>
<td>0.3</td>
<td>0.5</td>
<td>0.1</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>0</td>
<td>0.1</td>
</tr>
<tr>
<td>8</td>
<td>0.1</td>
<td>0.1</td>
<td>0</td>
</tr>
</tbody>
</table>

The mesh is automatically generated and divides the model into 16,000 elements, where 3,500 are shells and 12,500 are solids. All elements in all load combinations converge.