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Bending Behaviour of Glulam Beams Reinforced with FRP

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Summary

This paper describes an experimental program which examines the reinforcement in flexure of glulam beams with three type of fibers, two natural, Curauà and Sisal and one synthetic, Vectran. Nine beams reinforced with fiber at the tension side and three unreinforced control beams were instrumented and tested to failure in a three-point bending configuration. The mechanical properties of reinforced beams are compared to those of unreinforced beams with regard to the load-deflection behaviour, failure mode, ultimate load capacity, stiffness and strain distribution. The experimental results demonstrated the beneficial effect of the proposed reinforcing solution in terms of strength, stiffness and ductility.

Keywords: glulam beams, fibers, reinforcement, bending tests.

Sommario

Il presente lavoro di ricerca tratta lo studio del comportamento di una trave in legno lamellare fibrorinforzato soggetta a flessione, mediante un approccio sperimentale. Sono state utilizzate tre tipologie di fibre, due naturali, Curaruà e Sisal ed una sintentica, Vectran. Sono state eseguite prove di laboratorio su nove campioni rinforzati nella zona tesa della trave e su tre campioni di controllo non riforzati. Ogni trave è stata sottoposta a due modalità di applicazione del carico, la prima in tre punti, la seconda in quattro . I risultati otteuti sono stati comparati in termini di carico-inflessione, modalità di rottura, rigidezza e distribuzione delle tensioni, mostrando gli effetti benefici che i materiali di rinforzo conferiscono alle travi.

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CHAPTER 1
WOOD AND SUSTAINABILITY

In recent times "sustainability" is one of the world's most talked words . The concept of sustainability embraces the preservation of the environment as well as issues such as the efficient use of resources, social progress, stable economic growth, and the elimination of poverty.

In the world of construction, buildings have the capacity to make a major contribution to a more sustainable future for our planet. The OECD (Organization for Economic Co-operation and Development), for instance, estimates that buildings in developed countries account for more than forty percent of energy consumption over their lifetime, incorporating raw material production, construction, operation, maintenance and decommissioning. Add to this the fact over half of the world's population now lives in urban environments so that sustainable buildings have become cornerstones for securing long-term environmental, economic and social viability.

Sustainable construction involves issues such as the design and management of buildings, materials performance, construction technology and processes, energy and resource efficiency in building, improvement to existing contextual conditions, interdependencies of landscape, infrastructure, urban fabric and architecture.

In the last few years a variety of terms are used to mean “green” in the construction industry, including green building, sustainable design, high performance building, whole building design, sustainable building and integrated design. With the environmental progress of the ‘70s and the green building movement of the ‘90s, sustainable building practices can be characterized as a broad cultural evolution of society's relationship to the built environment.

Combining the various definitions provided in recent years , we define green building as a philosophy and associated project and construction management practices that seek to minimize or eliminate impacts on the environment, natural resources, and non-renewable energy sources to promote the sustainability of the built environment; increase the health, wellbeing and productivity of occupants and whole communities; cultivate economic development and financial returns for developers and whole communities, and apply life-cycle approaches to community planning and development.

1.1 The origin of green building

When did designers first become in green building? Today, we are still at the beginning of the Eco construction movement, as solar panels, renewable materials, and efficient design are still being introduced into the mainstream. Tomorrow, green building could be the norm.

Figure 1.1 The Brundtland Commission Report

The sustainability concept has been outlined in its current form in the '80s, as a result of a process initiated by a group of economists. In 1984, in Stockholm, they were held a symposium entitled "Integrating Ecology and Economics" who started a debate between economists and ecologists. The result was the the Brundtland Report, in October 1987, a document which coined and defined the meaning of the term "Sustainable Development", which then led the Rio Conference in 1992 and The Kyoto Protocol in 1997. Among those who gave an important contribution to the evolution of the concept of sustainability must remember the prof. Enzo Tiezzi, professor at the University of Siena. According Tiezzi the "sustainable city” is the challenge of our day.

Later, in 1994, the European Community promoted the First European Conference on Sustainable Cities held in Aalborg, Denmark, which resulted in the Aalborg Charter, signed by numerous European local administrations; with this act local governments pledged to adopt the Agenda 21, a plan promoted by the United Nations during the Rio Conference in 1992 to pursue a development planning of cities and durable and sustainable territories.

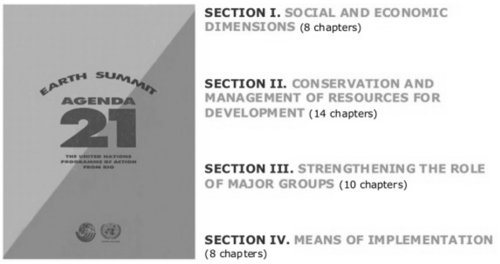

Figure 1.2 Agenda 21

Agenda 21 is a leading paper for sustainable development, which is to be seen as an environmental-political action programme for the 21st century at a local, regional and also global level. Agenda 21 comprises 359 pages and 40 chapters on social and business aspects, covering everything from the conservation of important resources, the development of resources, to an agreed package of action to be taken.

The provisions, strategies and conventions agreed on in Rio de Janeiro in 1992 formed the basis for a consensus in 1997 at a top-level conference in December 1997 in Kyoto, Japan. There a protocol was adopted in which for the first time, binding commitments for the emission of

Figure 1.3 Partecipation's map of Kyoto Protocol (UNEP GEO Data 2010)

anthropogenic greenhouse gases in the industrial states were determined. This protocol is known as the Kyoto Protocol and stipulates that industrialised countries reduce their mutual greenhouse emissions by at least 5% compared to the 1990 level within a time period from 2008 to 2012.

1.2 Green building and wood

Few building materials possess the environmental benefits of wood. It is not only one of the most widely used building material but also one with characteristics that make it suitable for a wide range of applications.

Over the past decade, the concept of green building has become more mainstream and the public is becoming aware of the potential environmental benefits of this alternative to conventional construction. Australian architect Alex de Rijke says, "The 18th century was about brick, the 19th about steel, the 20th about concrete, and the 21st century is about wood."

Much of the focus of green building is on reducing a building's energy consumption and reducing negative human health impacts. Wood has many advantages over traditional building materials such as concrete or steel, including low embodied energy, low carbon impact and sustainability.

Embodied energy refers to the quantity of energy required to harvest, mine, manufacture, and transport to the point of use a material or product. Wood, a material that requires a minimal amount of energy-based processing, has a low level of embodied energy relative to many other materials used in construction. The sun provides the energy to grow the trees from which we produce wood products; instead fossil fuels are the primary energy source in steel and concrete manufacture.

The role of carbon in global climate change and its projected negative impact on ecosystem sustainability and the general health of our planet have never been more elevated in the public's consciousness. Forests play a major role in the Earth's carbon cycle. The biomass contained in our forests and other green vegetation affects the carbon cycle by removing carbon from the

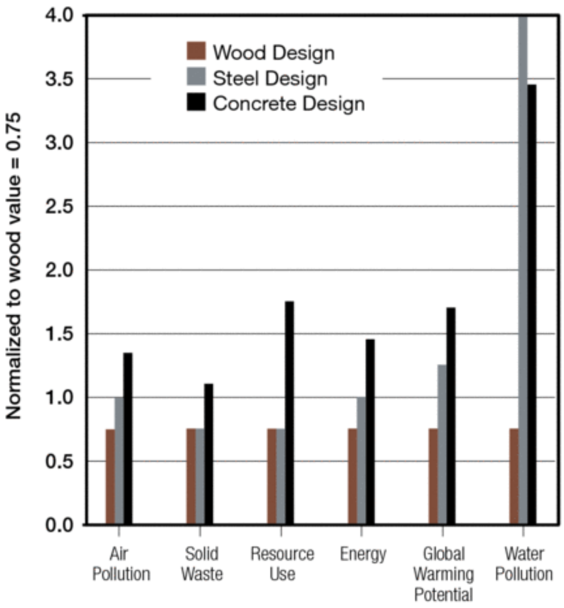

Figure 1.4 Embodied effect relative to the wood design across all measures

atmosphere through the photosynthesis process. Trees absorb carbon dioxide as they grow. When trees are made into building materials, that carbon dioxide remains sequestered in the finished products. When wooden building materials reach the end of their useful life, they are often be repurposed or recycled into new products. All that stored carbon dioxide is kept out of the atmosphere.

A study by Architecture And Design and published in the Journal of Sustainable Forestry finds that the world's forests contain more than 400 billion cubic yards of wood, but relatively little of that is turned into wooden building materials. Globally, there is a virtually inexhaustible supply of wood. For this reason, unlike metals and fossil-fuel-based products (such as plastics), our forest resource is renewable and with proper management a flow of wood products can be maintained indefinitely. However, the sustainability of this resource requires forestry and harvesting practices that ensure the long-term health and diversity of our forests.

Wood as a construction material has gained support of many builders and architects thanks to new technologies. The most promising is glued laminated timber (GLT), a process that resembles plywood but on a larger scale. They are almost as strong as steel, retain their static strength and shape indefinitely and allow the transfer of loads on all sides. Weak point of this kind of technology is the presence in large amounts of synthetic glues which make the material highly polluting and especially not recyclable. From here the need to study the process of innovation in a global sense, as also requested by the European Environmental Policy and the UNI EN ISO

14040, which emphasise the importance of analysis of the life cycle or life cycle Analysis (LCA).
It is a useful tool to measure and compare on a scientific basis the impacts of industrial production processes, during the lifecycle, to select the solutions that enable preservation of resources, the reduction of emissions into the

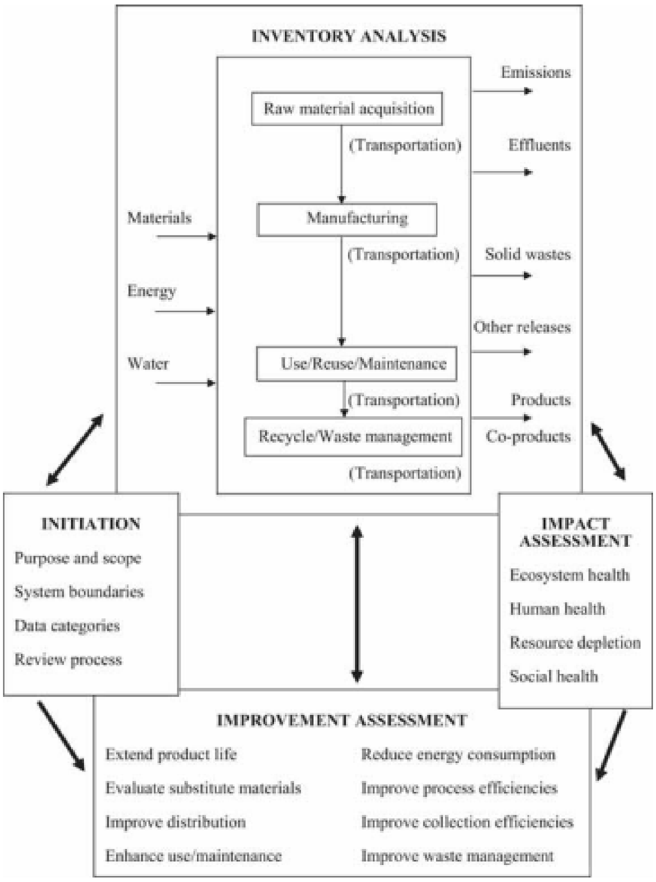

Figure 1.5 Life Cycle Assessment

environment, in order to sustainable development.
There are four linked components of LCA:

- Goal definition and scoping: identifying the LCA's purpose and the expected products of the study, and determining the boundaries (what is and is not included in the study) and assumptions based upon the goal definition;
- Life-cycle inventory: quantifying the energy and raw material inputs and environmental releases associated with each stage of production;

- Impact analysis: assessing the impacts on human health and the environment associated with energy and raw material inputs and environmental releases quantified by the inventory;
- Improvement analysis: evaluating opportunities to reduce energy, material inputs, or environmental impacts at each stage of the product life-cycle.

With regard to the characteristics of timber structures, particular relevance resides in the last two stages. The analysis of the impacts in fact has the aim to highlight the magnitude of the environmental changes resulting from releases into the environment and the consumption of resources, caused by productive activities. The LCA methodology consists in assigning specific known environmental effects, in order to quantify the contribution of the process considered. The fourth stage allows the choice of the necessary actions to correct the production system, or to redesign it. The interaction with the economic sphere is in this stage closer than in previous, because it is the assessment of the investment to bring out the best compromise.

1.3 Origin and development of FRP Glulam

From the historical point of view Glulam was born to overcome the size limitations of the timber from which are derived the beams. From a single stem is impossible to obtain elements of section and length necessary to allow coverage of large lights. In addition, the typical development of the stems does not allow to obtain curved beams of adequate cross-section.

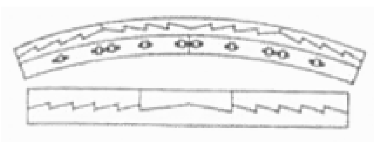

Figure 1.6 Sawtooth junction

The first problem is obviated through the realization of beams composed, more or less effectively cooperating, for example, sawtooth junction. The second problem was addressed for the first time in the sixteenth century, when it developed the idea of using the wood by assembling various parts to obtain roof sticks and arches.

The first attempt was to Philibert Delorme in France, who join by grain nailing more tables in superposed layers giving approximately the shape of the arch desired, and then shaping the top surface.


Figure 1.7 Grain nailing

But a radical change came from combination between the technique of lamination of the wood and the technique of bonding. The author of this transformation was Otto Freidrich Hetzer , in Weimar, Germany . In the early 20th century he proposed glued laminated (Glulam) timber elements by a strategic application of slender sawn timber pieces. He combined small section pieces producing elements of almost unlimited size and overcoming some formal and technical limitations associated to timber construction.


Figure 1.8 Glue laminated timber

The restrictions on the use of steel in construction during the World War II also helped the development of this new product, which knew two great dated developments. First one was in 1940 with the emergence of the first synthetic glues, and the second was in 1980 with the normalization of the marketing of various products used in the construction industry, including the Glulam timbers.

In Italy the introduction of laminated wood as alternative building system began in the Alpine region which has a strong tradition of wood culture, the South Tyrol. And especially in Val Pusteria, around 1960, that the lamellar, imported from neighboring Austria, makes his first appearance. It was mainly used in the reconstruction of the barns to replace the large ridge beams, which were hard to find in the local market. Then in 1970, the company Holzbau planted in Bressanone an establishment and began the first production of laminated wood in our country.

Construction in Glulam increased significantly in the early 2000s, partially driven by the green building movement but also due to better efficiencies, product approvals, and improved marketing and distribution channels. Hundreds of impressive buildings and other types of structures built around the world show the many advantages this product can offer to the construction sector. The European experience shows that this kind of construction can be competitive. Easy handling and a high level of prefabrication facilitate rapid project completion. Good thermal insulation, good sound insulation and good performance under fire and against seismic actions are added benefits that come as a result of the massive wood structure.

Figure 1.9 Bodegas Protos winery, Peñafiel, Spain

The idea of reinforcing glulam beams came in response to the need to improve the mechanical properties of strength and stiffness and to increase the reliability of this type of structural element. The inventor of the FRP reinforced wood technology is Dr. Dan Tingley. Tingley has conducted extensive research into the many aspects of FRP reinforced wood, particularly with glulams and owns over 24 patents worldwide.

Metallic reinforcement is one of the most common reinforcing materials for timber beams, which includes steel bars, steel strips, steel or aluminum plates, and even high strength steel cords. This kind of metallic reinforcement was used in the majority of the early work especially from 1960's. Steel reinforcement for timber structures appears to be both structurally efficient and cost effective. More recently FRP was used as structural reinforcement for timber beams, in the form of sheets, plates, strips and bars. Most recent focus has been on the reinforcement of wood using basalt fiber materials, since it also comes from natural material and has great economic interest due to the much lower price compared to carbon fiber. Natural fiber as a sustainable material was also introduced as the reinforcement of timber structures. FRP or natural fiber materials as reinforcement usually results in a lightweight and high mechanical performance system. Another advantage of FRP reinforcement is its better corrosion resistant performance compared to steel reinforcing materials.

Most of the existing research showed quite positive effects upon the flexural behavior of timber beams by the introduction of the reinforcing materials. Besides the improvement of flexural strength and stiffness, the failure mode would be changed from brittle tension failure in the unreinforced timber beams to a ductile compression failure for the adequately reinforced ones, which is quite important for a safe design.

Furthermore, many authors carried out theoretical and numerical analyses, which were well validated by the experimental results.

Fiorelli and Dias presented a deterministic model to calculate the stiffness and strength of fiber-reinforced solid timber beams. The stiffness was based on the transformed section concept. To calculate the mode of rupture, the model considers rupture by compression of the upper fibers or rupture by straining of the lower fibers. To evaluate the ultimate moment, the model considers the ultimate tensile and compressive strength of the lumber. This model is based on the hypothesis of Navier/Bernoulli (plane sections remain plane after straining). A comparison of the experimental and theoretical results demonstrated very similar values of strength and stiffness.

Borri conducted a theoretical and experimental study on carbon fiber reinforced polymers (CFRP) reinforced old wood beams with different reinforcement layouts and materials.

Romani and Blab presented a design model for fiber-reinforced glulam beams. In this work, the authors showed different rupture moduli for the reinforced glulam beam. They experimentally tested 10 x 30 cm glulam beams reinforced with carbon and aramid fibers, comparing their experimental results of the moment of rupture with their theoretical results. The authors stated that the proposed calculation model was quite conservative, showing a difference of approximately 35% below that of the experimental results.

Lindyberg and Dagher proposed a non-linear probabilistic model for the reinforced glulam beams, named the reinforced laminated model, which can predict the reinforced glulam modulus of elasticity (MOE) and the flexural strength. This work has two principal components. The first part is a deterministic numeric model that calculates the curve of load-deflection of the reinforced beam. This model is based on the Moment Curvature (M-φ), method previously used to analyze beams of concrete. The second part incorporates the deterministic model into a probabilistic model. For the development of the deterministic model inside of the probabilistic it was used the Monte Carlo computational simulator. In this work it is assumed a concept that was presented by (Buchanan, 1990) where the timber, when submitted to tensile efforts, presents an elastic-linear behavior, and when submitted to compression efforts the timber presents an elastic linear behavior and a nonlinear inelastic behaviour.

As noted in some research the addition of the tension reinforcement could arrest crack opening, confine the local rupture and bridge the defect of wood in the tension zone. As a result, it would remarkably increase the extreme fiber tensile strain (EFTS) of timber beams at failure. For this reason, an amplification factor was introduced into the bending strength of wood by Gentile.

Raftery and Harte developed a non-linear numerical model for FRP reinforced glulam beams, which could be used to optimize the FRP reinforced glulam beams in relation to loading configurations, geometric arrangements, lamination lay-up and quality, mechanical properties of the reinforcement and reinforcement ratio.

CHAPTER 2
THE WOOD

The wood, there's plenty of it, it's relatively cheap, it's environmentally friendly, it's warm and strong, it lasts hundreds or even thousands of years, and can be use for everything, from building bridges to making paper or heating home. The wood is one of the most useful and versatile material on the planet, with many thousands of different uses.

2.1 The properties

Strength

The strength of wood varies between different species, but also within a species, and within a tree. The inner structure of a tree makes wood what it is, how it behaves, and what we can use it for. Physically, wood is strong and stiff but, compared to a material like steel, it's also light and flexible. It has another interesting property too. Metals, plastics, and ceramics tend to have a fairly uniform inner structure and that makes them isotropic: they behave exactly the same way in all directions. Wood is different due to the wood grain. Wood has very good compression and tension performance in the direction of grain, but is particularly weak against force that pulls the grain apart. For that reason we say wood is anisotropic,

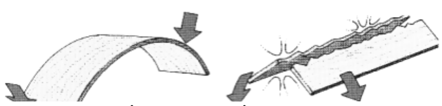

Figure 2.1 Anisotropy

which means a lump of wood has different properties in different directions. These different strengths relate to environmental factors, such as climate and rainfall, and site factors such as ground conditions and forest management practices. In order to build safely and efficiently with timber, engineers need to have information about the level, and variability, of the strength properties. This is achieved by a combination of testing work, to establish the basic information, to regulate, standardise, and provide confidence in the strength values to be used in design.

Durability

Wood is a durable material, when properly maintained it can last hundreds of years, it is resistant to heat, frost, corrosion and pollution. The only factor that needs to be controlled is exposure to weathering. In fact, we should extend the term durability and refer to it as "natural durability", because it relates directly to the timber's own inherent ability to resist attack by biological agencies. It's subject to the natural forces of decay through a process known as rotting, in which organisms such as fungi and insects such as termites and beetles gradually nibble away the cellulose and lignin and reduce wood to dust.

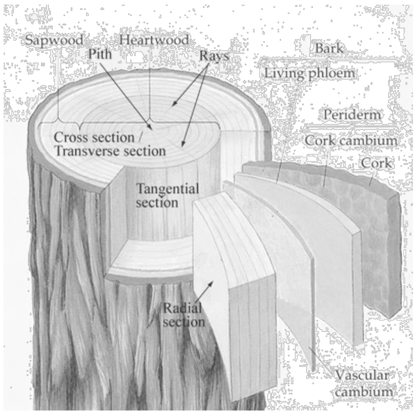

Figure 2.2 Wood's structure

Furthermore, the concept of natural durability in wood relates not to the entire tree, but only to the older, central portion of the tree trunk which is known as its "heartwood". The younger, outer band of wood tissue that actively taking part on the growing life of the tree, is called its "sapwood". All trees that have grown beyond a certain age, that will vary, depending upon climate, geographical location and forest type, will close down the inner part of the trunk and convert it to "heartwood", while the outer part remains active as "sapwood". This process continues as long as the tree is growing and expanding: so that the heartwood zone gets bigger, while the sapwood zone remains at much the same during the tree's adult life. The natural durability of the heartwood of many of the commercial timbers that we commonly use, is rated in respect of an established and agreed scale: with the most long-lasting timbers being classified as "Very Durable"; and the next best as "Durable"; followed down the scale by "Moderately Durable", "Slightly Durable" and lastly, "Not Durable". The thing to bearing in mind is that that that classification concern only the heartwood of the, all sapwood of all wood species is rated as "Not Durable".

Wood and water

Perhaps the most important aspect of woodworking deals with the relationship between wood and moisture. A fundamental fact is that wood is hygroscopic. This means that wood, almost like a sponge, will gain or lose moisture from the air based upon the conditions of the surrounding environment. But not only does wood gain or lose moisture, but it will also expand or contract according to the magnitude of such changes; and it is this swelling and shrinking in finished wood products that is responsible for malfunctions in woodworking.

When a tree is first felled, it is considered to be in the green state, and contains a very large amount of moisture. This moisture exists in two different forms: as free water that is contained as liquid in the pores of the wood, and as bound water that is trapped within the cell walls. Once a piece of wood is cut and exposed to the air, it will immediately begin losing free water. At this point, the wood does not contract or otherwise change in dimension since the fibers are still completely saturated with bound water. It is only once all the free water has been lost that the wood will reach what is called the fiber saturation point. Below the FSP, the wood will then begin to lose moisture in the form of bound water, and an accompanying reduction in the wood's volume will occur. At this point, the wood is no longer considered to be in the green state, but is now in a state of drying. The amount of water in a given piece of wood is expressed as a percentage of the weight of the water as compared to its ovendry weight.

Wood and fire

When the temperature of wood rises to 100 C, water begins to evaporate from it. The thermal softening of dry wood begins at a temperature of about 180 C and reaches its maximum between 320 C and 380 C. Then the lignin, cellulose and hemicellulose in the wood begin to disintegrate. The softening of moist wood begins earlier, at about 100 C.

The ignition temperature of wood is affected by how long it is exposed to heat. Wood usually ignites at 250 – 300 C. After ignition, the wood begins to carbonise at a rate of 0.8 mm per minute. Fire progresses slowly in a solid wood product, as the layer of carbon created protects the wood, and slows down the increase in temperature of the wood's inner parts and thus the progress of the fire.

Wood and Energy

Wood is probably the most important renewable energy source known to man. The growth in world consumption of energy derived from fossil fuels resulted in the use of energy that is insecure, expensive and extremely bad for the environment. This has led many countries to consider the need for profound changes, including the intensification of use of other sources of energy, especially renewable energy, including wood.

In the energy field, wood traditionally in the form of firewood has been the first source of energy, initially employed for heating and the preparation of food. Today, wood continues to take its place in the world's energy matrix, to a greater or lesser extent, depending on the region. Its use is affected by variables such as: the level of development in a country, availability of forests, environmental questions and how it competes economically with other energy sources such as oil, natural gas, hydroelectricity, nuclear energy etc.

Wood, in its simplest form as firewood is a vital fuel for the preparation of food for an enormous number of families and communities in various parts of the planet. It is estimated that, for every six persons, two use wood as their main source of energy, particularly families in developing countries, who use wood to sustain processes such as drying, cooking, fermentation, the production of electricity etc. (FAO, 2003). Although at a comparatively smaller volume, in developed countries wood also has a part to play as a source of energy. In such conditions, its use is becoming important as an environmentally healthier energy source and potential alternative to fossil fuels, its use leading to a reduction in emissions of greenhouse gases.

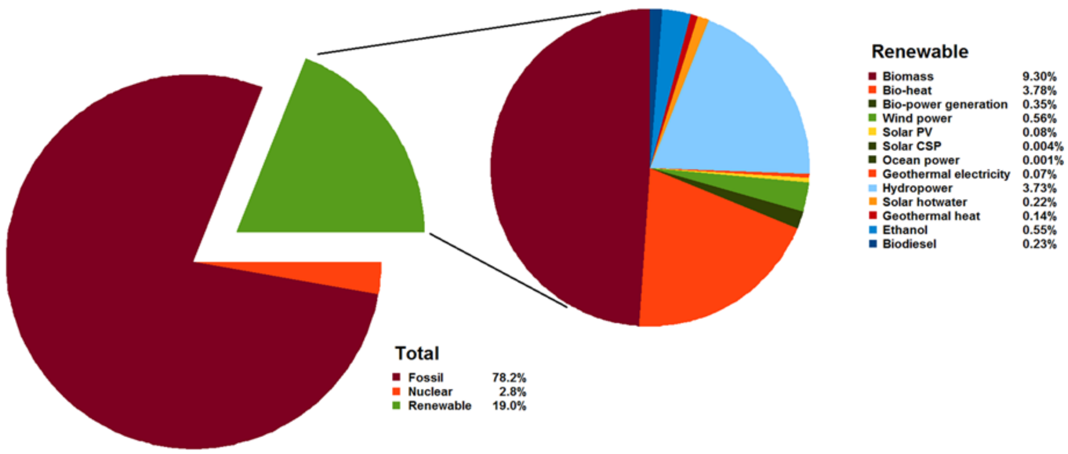

Figure 2.3 Total World Energy Consumption by Source 2011

Also the wood is a relatively good heat insulator, which comes in handy in building construction. Although it can absorb sound very effectively, but wooden objects can also be designed to transmit and amplify sounds. Wood is generally a poor conductor of electricity but, interestingly, it's piezoelectric, an electric charge will build up on wood if you squeeze it the right way.

Cost effective

Much like other raw materials, the price of different wood species will change over time. Additionally, wood prices will also vary depending on location and import process. But in general, comparative studies of the economics indicate that, in terms of direct building expenses, timber frames are consistently the most cost-effective solution. There are many factors to consider when comparing the economics of different construction systems including the complexity of the layout, site, builder experience, and relative material prices at the time of building.

2.2 Wood processing

Harvesting

Growing trees for human use is called silviculture. How wood is harvested depends on chance trees are growing in plantations, where there are hundreds or thousands of the same species, generally of similar age or in mature forests, where there's a mixture of different species and trees of widely differing ages.

Planted trees may be grown according to a precise plan and clear-cut when they reach maturity. A drastic approach like that makes sense if the trees are a fast-growing species planted specifically for use as biomass fuel, for example.

Sometimes trees have their bark and small branches removed in the forest before being transported away for further processing, but they can also be removed intact, with the entire processing done offsite. It all depends on the value of the tree, the growing conditions, how far away the lumber yard is, and how easy the tree is to transport.

Seasoning

A freshly cut tree has to be completely dried out or seasoned before it can be used. Dry wood is less likely to rot and decay, it's easier to treat with preservatives and paint, and it's much lighter and easier to transport. Dry wood is also much stronger and easier to build with and if a tree is destined for burning as firewood, it will burn more easily and give out more heat if it's properly dried first.

Typically wood is dried either in the open air, which takes anything from a few months to a year, or in vast heated ovens called kilns, which cuts the drying time to days or weeks. Seasoned wood is still not completely dry: typically its moisture content varies from about 5–20 percent, depending on the drying method and time.

Preserving and other treatment

In theory, wood might last forever if it weren't attacked by bugs and bacteria; preservatives can greatly extend its life by preventing rot. Different preservatives work in different ways. Paint, for example, works like an outer skin that stops fungi and insects penetrating the wood, but sunlight and rain make paint crack, leaving the wood open to attack underneath. Creosote, another popular wood preservative, is a strong-smelling, oily brown liquid usually made from coal-tar. Unlike paint, it is a fungicide, insecticide, miticide, and sporicide: in other words, it works by stopping fungi, insects, mites, and spores from eating or growing in the wood.
Different kinds of treatment help to protect and preserve wood in other ways. Wood is so plentiful and burns so well that it has long been one of the world's favorite fuels. That's why fire-protection treatment of wooden building products is so important. Typically, wood is treated with fire retardant chemicals that affect the way it burns if it catches fire, reducing the volatile gases that are given off so it burns more slowly and with greater difficulty.

Cutting

Trees need a bit more work in the sawmill to turn them into timber. Flat pieces of wood can be made from trees by cutting logs in two different directions. Usually it is typically cut in one of three ways: quarter sawn, rift sawn or plain sawn. The result is a particular orientation of the growth rings on the end grain of the board and is what defines the type of timber. The type of cut also determines the wood’s mechanical properties.

2.3 The defects

One of the biggest challenges of working with timber is learning to work within the constraints of a timber's. The fact that timber is not a manufactured material like iron or cement but is a natural product which has been formed by years of growth in the open where it has been exposed to various adverse conditions of wind and weather, make it peculiarly liable to defects of different kinds.

A defect is simply an abnormality or irregularity found in wood. There are innate defects caused by the natural characteristic of wood to shrink or expand in response to moisture. And, there are artificial and mechanical defects caused by incorrect sawing or machining, improper drying or handling and storage. Defects may be responsible for reducing wood's economic value, lowering its strength, durability and usefulness and in some cases, causing its decay.

Some of the more common wood defects all woodworkers face include:

- *Fungal damage*: fungi generally damages timber or wood by discoloration and/or decay. The resulting wood is generally weaker or of a different color than is typical for that species.
- *Insect defects*: there are a number of insects that eat wood. Many other insects use wood as a nesting place for their larvae which results in holes and tunnels in the wood. The damage they cause ranges from minor to catastrophic.
- *Knots:* a knot is the base of a branch or limb that was broken or cut off from the tree. The portion of the remaining branch receives nourishment from the stem for some time and it ultimately results in the formation of dark hard rings known as knots. As the continuity of wood fibers are broken by knots, they form a source of weakness.
- *Shake*: a lengthwise crack or separation of the wood between the growth rings, often extending along the board's face and sometimes

below its surface. Shakes may either partly or completely separate the wood fibers. The separations make the wood undesirable when appearance is important. Although this is a naturally occurring defect possibly caused by frost or wind stress, shakes can also occur on impact at the time of felling and because of shrinkage in the log before conversion.

- *Split*: a split is a rupture or separation in the wood grain which reduces a board's appearance, strength, or utility. One of the more typical ruptures of this type is called ring shake. In a ring shake (also known as cup shake or wind shake), the rupture runs parallel to the growth rings. It's not easily detected in green logs and lumber, but only becomes apparent after drying. It's caused by any one of numerous factors, including bacteria, tree wounds, tree age, and environmental conditions.
- *Wane*: the presence of bark or the absence of wood on the corners or along the length of a piece of lumber. Wane, in the form of bark, is more commonly associated with rough milled lumber. In the case of construction lumber, it can be bark or missing wood.
- *Bowing*: a curvature formed in the direction of the length of timber. A bowed board is flat, but bent, like a road going over a hill.
- *Check*: a check is a crack which separates the fibers of wood. It does not extend from one end to the other. It occurs across the growth rings and is usually caused by poor or improper drying processes.
- *Crook*: where the board remains flat, but the ends move away from the center. Another type of warp.
- *Twisting*: where the board curves in length and width like a propeller.

- *Cupping*: where the face of a board warps up across its width such that if one looks at the end of the board, it will look like a shallow letter "U." Is common with plain-sawn lumber.

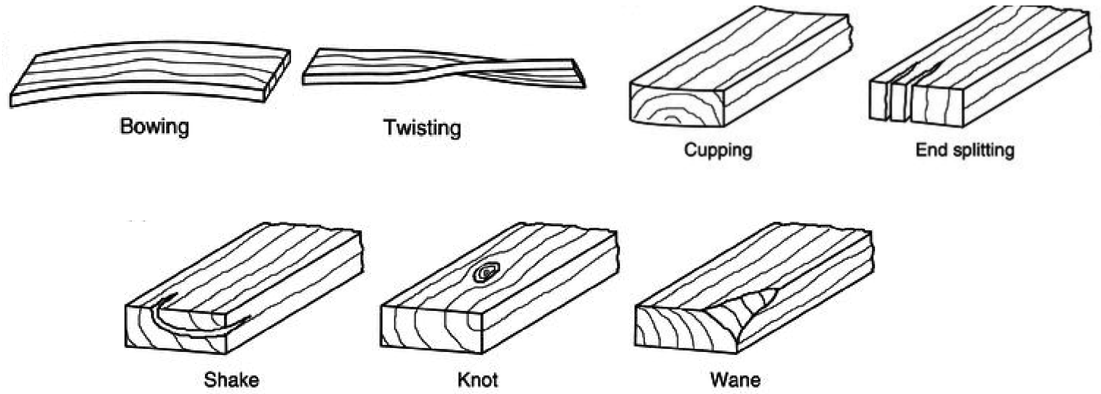

Figure 2.4 Wood's defects

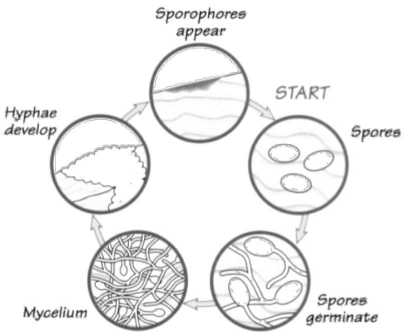

Figure 2.5 Wood rotting fungus- life cycle

Figure 2.6 Fungal damage, discoloration of sapwood

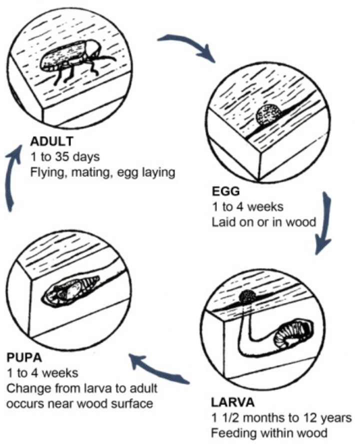

Figure 2.7 Beetle's life cycle

Figure 2.8 Beetles damage

CHAPTER 3
COMPOSIT MATERIALS

A composite material is made by combining two or more materials, often ones that have very different properties. The two materials work together to give the composite unique properties, they do not dissolve or blend into each other. Most composites are made of just two materials. One is the matrix or binder. It surrounds and binds together fibres or fragments of the other material, which is called the reinforcement.

Wood is an example of natural composite, it is made from long cellulose fibres, a polymer, held together by a much weaker substance called lignin. The two substances, lignin and cellulose, together form a much stronger one.

People have been making composites for many thousands of years. One early example is mud bricks. Mud can be dried out into a brick shape to give a building material. It has good compressive strength, but it breaks quite easily if you try to bend it, that means that it has poor tensile strength. Straw seems very strong if you try to stretch it, but you can crumple it up easily. By mixing mud and straw together it is possible to make bricks that are resistant to both squeezing and tearing and make excellent building blocks. Another ancient composite is concrete. Concrete is a mix of aggregate, small stones or gravel, cement and sand. It has good compressive strength. In more recent times it has been found that adding metal rods or wires to the concrete can increase its tensile strength.

The biggest advantage of modern composite materials is that they are light as well as strong. By choosing an appropriate combination of matrix and reinforcement material, a new material can be made that exactly meets the requirements of a particular application. Composites also provide design flexibility because many of them can be moulded into complex shapes. The downside is often the cost. Although the resulting product is more efficient, the raw materials are often expensive. Composites have also inherent benefits that are of interest to green builders like durability, insulation and re-use, they can incorporate bio & recycle content and offer material reduction; they offer functional applicability to green building programs.

3.1 The reinforcement

The reinforcing phase provides the strength and stiffness. In most cases, the reinforcement is harder, stronger, and stiffer than the matrix. The reinforcement is usually a fiber or a particulate.

Usually fiber has a length that is much greater than its diameter and can be divided into two main categories: particulate and continuous fiber. Continuous fiber composites normally have a preferred orientation, they will often constitute a layered or laminated structure, while particulate generally have a random orientation. They tend to be much weaker and less stiff than continuous fiber composites, but they are usually much less expensive because they contain less reinforcement.

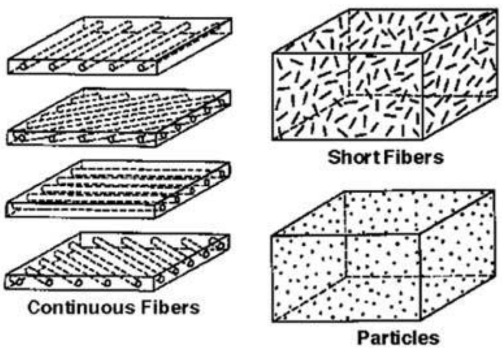

Figure 3.1 Classification of fibers

Fibers produce high strength composites because of their small diameter. As a general rule, the smaller the diameter of the fiber, the higher its strength, but often the cost increases as the diameter becomes smaller. In addition, smaller diameter high strength fibers have greater flexibility and are more amenable to fabrication processes such as weaving.

3.1.1 Vectran fiber

First produced in 1990, Vectran is a high-performance multifilament and it is the only commercially available melt spun LCP fiber in the world. Vectran is an aromatic polyester spun from a liquid crystal polymer (LCP) in a melt extrusion process. LCP polymer molecules are stiff, rod-like structures organized in ordered domains in the solid and melt states. These oriented domains lead to anisotropic behavior in the melt state, thus the term "liquid crystal polymer." The fiber is formed by melt extrusion of the LCP through fine diameter capillaries, during which the molecular domains orient parallel to the fiber axis. The structure's high degree of orientation translates to excellent fiber tensile properties.

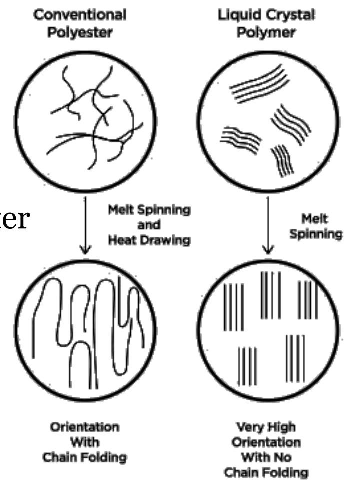

Figure 3.2 Schematic of molecular chain structure of fiber

With conventional polyesters, the molecular chains are random and flexible. Fibers spun from such materials must be further oriented, to obtain higher tensile properties. Vectran's highly oriented structure is locked in directly during the melt-spinning process, thanks to the molecular structure and liquid crystalline nature of the starting polymer. It is different from other high-performance fibers such as aramid and ultra-high molecular weight polyethylene (HMPE) because it is thermotropic, it is melt-spun, and it melts at a high temperature.

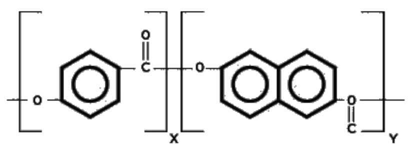
Figure 3.3 LCP molecular structure

Vectran's remarkable mechanical performance combined with the other unique properties permit it to be used for a variety of purposes, they are used in aerospace, ocean exploration and development, electronic support structures, the recreation and leisure industry, safety materials, industrial applications, ropes and cables, composites, protective apparel and high-pressure inflatables.

The first use of Vectran fiber was for demanding and specialized military applications. In fact in July 1997 the airbags above, made with Vectran fibers were deployed to cushion the Pathfinders successful landing on the surface of Mars. But Vectran fiber brings unique solutions also to industrial applications. Stability to most chemicals allows the manufacture of chemically resistant packings and gaskets. Users of protective apparel such as gloves and workwear benefit from excellent cut resistance, elevated temperature resistance, and durability to multiple wash/dry cycles. Finally Vectran fiber is also an excellent candidate for printed circuit boards, fiber optic strength members, and conductor reinforcements. High dielectric strength coupled with elevated temperature resistance and outstanding moisture resistance provide new levels of electrical efficiency in prevention of current leakage.

Figure 3.4 Vecran fiber, Kuracay America

The Vectran fiber offers different options in design and material selection. Vectran HT fiber offers benefits for applications requiring high strength, vibration damping, low moisture absorption. Vectran NT fiber is a high modulus thermoplastic matrix fiber for applications requiring high impermeability, excellent property retention over a broad temperature range,

Material	Density (g/cm3)	Tensile Strength (GPa)	Specific Strength (km*)	Tensile Modulus (GPa)	Specific Modulus (km**)
Vectran™ NT	1.4	1.1	79	52	3700
Vectran™ HT	1.41	3.2	229	75	5300
Vectran™ UM	1.4	3.0	215	103	7400
Titanium	4.5	1.3	29	110	2500
Stainless Steel	7.9	2.0	26	210	2700
Aluminum	2.8	0.6	22	70	2600
E-Glass	2.6	3.4	130	72	2800
Graphite (AS4)	1.8	4.3	240	230	13000

*Specific strength = Strength/Density (also divided by force of gravity for SI units). Also known as breaking length, the length of fiber that could be held in a vertical direction without breaking.
** Specific modulus = Modulus/Density (also divided by force of gravity for SI units). This measure increases with increasing stiffness and decreasing density.
(KAI data)

Table 3.1 Comparison of properties of various engineering materials_Kuraray America and low moisture absorption. Vectran UM offers the highest modulus without sacrificing tensile strength.

3.1.2 Natural fibers

The use of composite materials dates from centuries ago, and it all started with natural fibres. In ancient Egypt some 3 000 years ago, clay was reinforced by straw to build walls. Later on, the natural fibre lost much of its interest. Other more durable construction materials like metals were introduced. During the sixties, the rise of composite materials began when glass fibres in combination with tough rigid resins could be produced on large scale. During the last decade there has been a renewed interest in the natural fibre as a substitute for glass, motivated by potential advantages of weight saving, lower raw material price, and 'thermal recycling' or the ecological advantages of using resources which are renewable. On the other hand natural fibres have their shortcomings, and these have to be solved in order to be competitive with glass. Natural fibres have lower durability and lower strength than glass fibres. However, recently developed fibre treatments have improved these properties considerably.

Most of the benefit are low specific weight, which results in a higher specific strength and stiffness than glass, that is important especially in parts designed for bending stiffness; it is a renewable resource, the production requires little energy, CO_2 is used while oxygen is given back to the environment; it is producible with low investment at low cost, which makes the material an interesting product for low-wage countries; thermal recycling is possible, where glass causes problems in combustion furnaces; it has also good thermal and acoustic insulating properties

3.1.2.1 Sisal

Within the total production of leaf fibers, sisal is the most important. Sisal is a hard fiber extracted from the leaves of sisal plants which are succulents that grow best in hot and dry areas. It is a member of the agave family, which are hardy plants of arid regions of Central America, Mexico and South West USA. The plants grow for 7 to 12 years and then produce a flower stalk 4 to 6 metres tall and die.

Figure 3.5 Agace Sisalana

The first harvest can be made when the plants are about two years old. The fiber is usually obtained by machine decortications in which the leaf is crushed between rollers and then mechanically scraped. The fiber is then washed and dried by mechanical or natural means. The dried fibre represents only 4% of the total weight of the leaf. Once it is dried the fibre is mechanically double brushed.

Sisal fibre is very long, with an average length of 0.6 to 1.2 m and it is creamy white to yellowish in colour. It is coarse and strong, durable and has the ability to stretch. It also has good insulation properties and it is highly resistant to bacterial damage and to deterioration in saltwater.

Figure 3.6 Sisal fiber

The tensile properties of sisal fibre are not uniform along its length. The root or lower part has low tensile strength and modulus but high fracture strain. The fibre becomes stronger and stiffer at mid-span and the tip has moderate properties. Table 2 shows the properties of sisal fibres as reported by different researchers.Note that except for the structure and properties of the natural fibre itself, experimental conditions such as fibre length, test speed, etc., all have some effects on the properties of natural fibres. Mukherjee and Satyanarayana studied the effects of fibre diameter, test length and test speed on the tensile strength, initial modulus and percent elongation at the break of sisal fibres. They concluded that no significant variation of mechanical properties with change in fibre diameter was observed. However, the tensile strength and percent elongation at the break decrease while Young's modulus increases with fibre length. With increasing speed of testing, Young's

Density (kg/m^3)	Tensile strength (MPa)	Tensile Modulus (GPa)	Maximum strain (%)	Diameter (µm)	Reference
1450	604	9.4–15.8	–	50–200	*Natural fibre-polymer composites*, K.G Satyanarayana, K Sukumaran, P.S Mukherjee, C Pavithran, S.G Pillai
1450	530–640	9.4–22	3–7	50–300	*Bibliography resource structure properties of natural cellulosic fibres, an annotated bibliography*, N. Chand, R.K Tiwary, P.K Rohatgi
–	347	14	5	–	*The interfacial bond strength of sisal–cement composites using a tensile test*, T.J Bessell, S.M Mutuli
1030	500–600	16–21	3.6–5.1	–	*Impact properties of natural fibre composites*, C. Pavithran, P.S Mukherjee, M Brahmakumar, A.D Damodaran
1410	400–700	9–20	5–14	100–300	*Theoretical modelling of tensile properties of short sisal fibre–reinforced low-density polyethylene composites*, G. Kalaprasad, K. Joseph, S. Thomas
1400	450–700	7–13	4–9	–	*Tensile properties of short sisal fibre reinforced polystyrene composites*, K.C Manikandan, S.M.D Nair, S. Thomas
–	530–630	17–22	3.64–5.12	100–300	*Structure and properties of some vegetable fibres, part 1. Sisal fibre*, P.S Murherjee, K.G Satyanarayana
1450	450–700	7–13	4–9	–	Short sisal fibre reinforced styrene–butadiene rubber composites, R.P Prasantha, M.L Kumar, G Amma, S Thomas

Table 3.2 Properties of sisal fibres reported by different researchers

modulus and tensile strength both increase but elongation does not show any significant variation. These results have been explained in terms of the internal structure of the fibre, such as cell structure, microfibrillar angle (20–25°), defects, etc. In rapid mechanical testing, the fibre behaves like an elastic body, the crystalline region shares the major applied load resulting in high values of both modulus and tensile strength. When the testing speed decreases, the applied load will be borne increasingly by the amorphous region. However, at very slow test speeds, the fibre behaves like a viscous liquid. The amorphous regions take up a major portion of the applied load giving a low fibre modulus and a low tensile strength. But at very high strain rates, the sudden fall in tensile strength may be a result of the presence of imperfections in the fibre causing immediate failure.

Unlike synthetic fibres, sisal is 100% biodegradable. Measured over its life-cycle, sisal absorbs more carbon dioxide than it produces. During processing, it generates mainly organic wastes and leaf residues that can be used to generate bioenergy, produce animal feed, fertiliser and ecological housing, at the end of its life cycle. By contrast synthetically produced fibres do not possess any of these traits. Moreover sisal plants reduce soil erosion through its extensive root system and contributes positively to watershed management. Sisal plants used as effective vegetative barriers to protect the crops lands and forests from predatory animals and intruders.

In the late 1930's, commercial plantations started in Brazil, and today Brazil is the major world producer of sisal with 130,000 tons/year. Sisal is the only crop that resists the semi-arid climate and which is economically feasible to the poor northeast region of the country where around 800,000 people depend on it. Besides Brazil sisal is also produced in Mexico (45,000 tons/year); China (36,000 tons/year); Tanzania (24,000 tons/year); Kenya (25,000 tons/year) and Madagascar (15,000 tons/year).

3.1.2.2 Curauá

Compared to other lignocellulosic fibers the curauá (Ananas erectifolius) fiber has been rarely studied. The plant is native to the Amazon where the Indians of that region have known it since the pre-Columbian era for making hammocks. There are four varieties of plants: white, purple, red, and bright white. The most common are purple curauá with purple-reddish leaves and white curauá with light green leaves and lesser growth than purple. For each curauá plant there are 20 to 24 leaves yearly, equivalent to 2 kg of fiber. The stalk of the plant reaches up to 1.5 m with upright leaves of 5 cm width, 0.5 cm thickness and approximately 1.5 m length.

Fiber processing consists of defiberizing the leaves followed by drying, softening, and lightening of the fibres manually or mechanically. Because

Figure 3.7 Curaua plant (a), bundle of fibers (b) and fibrils observed by scanning electron microscopy (c)

they are soft and resistant, the curauá fibers are currently employed as raw material in the textile and automotive industries, sack manufacturing, thread production, etc. In Brazil, curauá fibers are mainly produced in the state of Para´ where local communities cultivate the fibers associated with other cultivations such as manioc, vegetables, and beans.

According to the study of R.V. Silva and E. M. F. Aquino, comparing white and purple curauá fibers, we can see close values to diameter and Young modulus; only the tensile strength was slightly superior for white curauá. Also, it is observed that the curauá fibers present lesser diameter and higher tensile strength and Young modulus when compared to sisal, jute, and coconut fibers. Moreover, the curauá fibers come nearest to glass-E fiber.

Fiber	Diameter (µm)	Tensile strength (MPa)	Young modulus (GPa)
Purple curaua	*49–93*	*665–1300*	*20–33*
White curaua	*60–100*	*859–1404*	*20–36*
Jute	200	393–773	26.5
Sisal	50–300	511–635	9.4–22
Coconut	100–450	131–175	4–13
E-glass	8–14	1800–3000	72–83

Table 3.3 Comparison of diameter, tensile strength, and Young modulus of different type of fibers

Mechanical resistance of lignocellulosic fibers is determined mainly by the fiber cellulose content. It can be observed that the chemical composition of the curauá fiber is closer to the sisal fiber. This is not surprising as both fibers are the result of plants with similar characteristics. Curauá and sisal fibers are also similar with regard to shape, length, and color.

	Curaua	Jute	Sisal	Coconut
Cellulose	70.7–73.6	61–71.5	67–78	36–43
Hemicellulose	9.9	13.6–20.4	10–14.2	0.15–0.25
Lignin	7.5–11.1	12–15	8–11	41–45
Pectin	–	0.2	10	3–4
Water soluble	–	1.1	16.2	–
Waxes	–	0.5	2	–
Spiral angle	–	8.0	20	41–45
Humidity	7.9	12.6	11.0	–

Table 3.4 Chemical composition of some vegetal fibers (wt%)

3.2 The matrix

The role of the matrix in a composite profile is partly to bind the reinforcement together, and partly to keep the reinforcement correctly positioned to optimal utilization of the mechanical properties. The major composite classes include organic, metal and ceramic matrix composed. The term organic matrix composite generally includes two classes of composites namely polymer and carbon composites.

Polymers make ideal materials as they can be processed easily and possess lightweight mechanical properties. Two main kinds of polymers are thermosets and thermoplastics.

Thermoset materials are those materials that are made by polymers joined together by chemical bonds, acquiring a highly crosslinked polymer structure. The highly crosslinked structure produced by chemical bonds in thermoset materials, is directly responsible for the high mechanical and physical strength compared with thermoplastics or elastomers materials. On the other hand is this highly crosslinked structure which provides a poor elasticity or elongation of this materials. One of characteristic parameter of thermosets materials are the gel point, which refers to the time when the material changes from an irreversible way-viscous liquid state to a solid state during the curing process. Once has been transferred the gel point the material stops flowing and it cannot be molded or processed grid. One of the negative aspects of thermosets is its no ability to recycle, because once they are crosslinked or cured it is impossible to return to a liquid phase material. Thermoset materials have the property of not melt or deforming in presence of temperature or heat before pass to a gaseous state to a liquid state. They are most suited as matrix bases for advanced conditions fiber reinforced

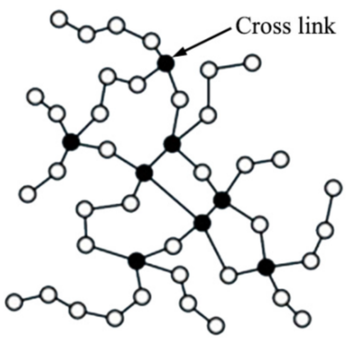

Figure 3.8 Thermoset polymer

composites. Examples of thermoset adhesives are epoxy resins, phenolic resins and unsaturated polyester.

Thermoplastic materials are those materials that are made of polymers linked by intermolecular interactions, forming linear or branched structures. The greater degree of mixing of the polymers greater the effort will be made to separate the polymers from each other, due to the intermolecular forces that holds together the polymer. Depending on the degree of the intermolecular interactions that occurs between the polymer chains, the polymer can take two different types of structures, amorphous or crystalline structures, being possible the existence of both structures in the same thermoplastic material.If the thermoplastic material has a high concentration of polymers with amorphous structures, the material will have a poor resistance to loads but it will have an excellent elasticity. But on the contrary, if the thermoplastic material has a high concentration of polymers with a crystalline structure, the material will be very strong and even stronger than thermoset materials, but with a little elasticity that provides the characteristic fragility of these materials. Examples of thermoplastic adhesive are acrylates and cyanoacrylates.

Figure 3.9 Thermoplastic polymer

3.3 Reinforced laminated timber

Nowadays, there is a large variety of products derived from wood and each of them has its own specificities. Glulam, or glue-laminated timber, are perhaps the engineered wood product most widely used in construction sector, essentially due to both its mechanical properties and industrialized manufacturing process. The defects of wood pieces used to produce Glulam material are eliminated or made irrelevant, leading to mechanical strength and modulus of elasticity higher than those of solid wood. Furthermore, its rigorous production results in very precise geometries and in highly controlled moisture content.

Glulam is made of single wood layers bonded together with superior wood adhesives and allows the production of parts with the desired shape and length.

The first benefit of glulam is that its main constituent, timber, grows out of the ground and does not need to be mined and subjected to the high energy demand manufacturing processes that steel and cement require. Of course there are also energy requirements for glulam manufacture in the felling, sawing, transportation, manufacture of the glue etc., but this is still far less than for steel and concrete.

Glulam is often chosen over steel or concrete for its appearance. Timber is often credited with creating a warm and comfortable feel in a building and there are many different species and treatments available all with their own character that can be adapted to suit requirements.

In addition timber has a good strength to weight ratio in comparison with steel and concrete. If you consider equivalent beam sizes for the same load bearing capacity in glulam and steel, glulam has approximately 1.5 – 2 times the strength to weight ratio of steel.

The durability of glulam will depend on its specification. Species of timber, type of glue and preservative type and application are all factors in the durability of glulam. Given the correct specification glulam can be used for the most onerous of conditions. One instance where glulam is chosen for its durability is in swimming pool roofs- this is a articularly corrosive environment with high humidity and chlorine levels and glulam provides a durable low maintenance solution.

Finally large section timber elements actually perform very well in fires. This is due to the way in which does not deform like steel. Additional fire protective finishes can be used to further increase the fire performan

The necessity to restore the design specifications of a determined structure, combined with cost, weight and environmental impact reduction makes the use of high performance composite systems, involving, either synthetic or natural materials, interesting. Fibre reinforced polymer (FRP) has been object of deep research, in order to confirm its capabilities on repairing and strengthening existing structures. The great confidence in this composite is grounded on its advantages such as: high stiffness and tensile strength, low weight, easy installation procedures, high durability (no corrosion), electromagnetic permeability and practically unlimited availability in terms of geometry and size. By applying a layer of fiber reinforcement bonded with the glued laminated timber beam with an appropriate adhesive, a high performance composite system is obtained, resulting on a significant increase of strength and bending stiffness of the structural element that each isolated material did not have before.

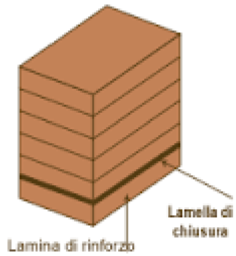

Figure 3.10 FRP Reinforced Glulam

CHAPTER 4
THE EXPERIMENTAL ANALYSIS

This chapter focuses on the experimental analysis of wood laminated beams reinforced with different kind of fibers synthetic and natural. The bending tests were made with and without reinforcement and the numerical results obtained from the analysis are compared among each other considering resistance and stiffness. The theoretical method take in consideration is the transformed section method. Its consists of transforming a straight section which contains more than one material, into another equivalent formed by a unique material. The stiffness and the displacements of the beams was calculated with this method.


Figure 4.1 Cross section

The experimental program was carried out with bending test for the verification of stiffness and strength of reinforced laminated timber beams of wood of the species Pinus Elliottii with two different kind of adhesive, polyurethane (PU) and emulsion polymer isocyanate (EPI) . The fibers used as reinforcement are the Vectran, Sisal and Curauá fibers.

4.1 Materials

4.1.1 Characterisation of the fibers

The natural fibers used as reinforcement, Curaua and Sisal, have not been subjected to laboratory testing. The mechanical properties of strength and stiffness are related to the research carried out by Mascia, Furlani and Vanali in 2010 according to the results obtained by Silva and Aquino in 2008. Instead, for the determination of the strength and stiffness values of Vectran HT fibers, tensile tests have been carried out by the FEC- Unicamp research group.

Vetran HT

Figure 4.2 Vectran 800g/m² (a), Vectran 400g/m²(b), Sisal 1393g/m² (c), Curauá (d)

The verification of the mechanical properties of resistance and stiffness of Vectran HT fibers was carried out by tensile test in nine specimens according to ASTM D2256 (2002)- Standard Test Method for Tensile Properties of Yarns by the Single-Strand Method.

The samples had a diameter of 0.23 mm, measured through a micrometer, and a length of 250mm, with 150mm of The free between claws and 50mm of the length attached to each claw.

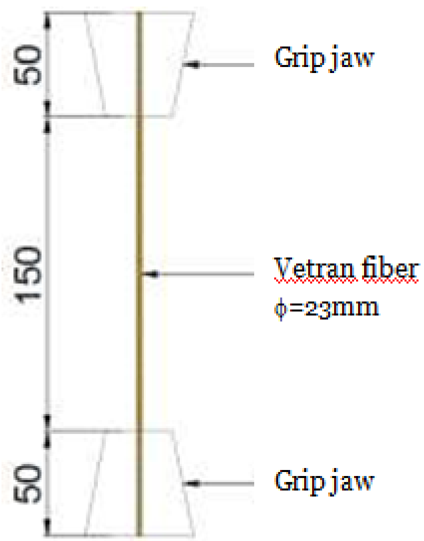

Figure 4.3 Arrangement of tensile test

For the test it was used a controlled universal testing machine, WDW 100e, which is a new kind of electronic universal testing machine produced by TIME-Shijin Group, and grip jaws with performance in the range of 0 mm to 7 mm of thickness of the test body.

Figure 4.4 Controlled universal testing machine, WDW 100e

To ensure a uniform distribution of tension between the yarns of the fiber, note 8 of the ASTM D2256 (2002) standard was followed, which recommends twisting the samples around their longitudinal axis. To calculate the number of turns it was used the equation:

$$n_g = \frac{43}{\sqrt{D}} \qquad [1]$$

where "n_g" is the number of rotations about the longitudinal axis of the fiber and "D" is the denier (weight in 9000m grams of yarn) of fiber that, according to Kuraray (2010), the Vectran fiber presents denier equal to 2.5. For the tests were applied 20 rotations in the fiber.

To prevent the twisted fiber sample from returning to its position without rotation and to facilitate its positioning in the test machine, the sample was trapped by its ends on a paper strip using masking tape. Before starting the test the paper was cut so as not to cause interference.

Figure 4.5 Body test

As required by ASTM D2256 (2002), the speed of the test was corrected so that fiber breaks occurred at a time between 20s ± 3s after the start of the test.

Data obtained from the traction test on Vectran HT fiber samples show that the fibers exhibit a very high average strength value and elastic modulus higher than fiber like glass, and more close to fibers such as carbon and steel.

Table 4.1 Resistance values and Modulus of elasticity obtained in the traction test in Vectran fibers according to ASTM D2256

Nome	E MPa	f_t MPa
T1	82500	3370
T2	117857	3370
T3	168000	4332
T4	137500	3370
T5	69444	2407
T6	142857	2888
T7	133333	4332
T8	150000	3370
T9	137931	4332
Média	126603	3530
Desvio	31832	681
Coef. var.	25%	19%

Material	Ultimate Tensile Strength* (MPa)	Tensile Modulus (GPa)
E-Glass	1103	44.8
S-Glass	1931	51.7
Kevlar-49	1448	75.8
Type HMS Graphite	1172	206.8
Type AS Carbon	1724	137.9
Emerging High Strain Graphite	2413	310.3
Aluminum (7075-T6)	572	68.9
Titanium (6A1-4V)	1103	113.8
Steel (4130)	1379	200.0

Table 4.2 Source: Advanced Composite Materials Technology Research Centre at The Hong Kong University of Science and Technology

The strength values and elastic modulus obtained are also greater than that then date of Kuraray America shown in the table 3.1. It is believed that the difference occurred because of the way the resistant section area was considered, and it is advisable for later work to review the adopted test method.

4.1.2 Preparation of fibers

For standard reinforcement application in the beams, the fibers were separated in batches before being applied as reinforcement. The batches containing Curauá fibers were assembled taking the weight of the fiber as a criterion, with fiber batches weighing 75g.
For the Vectran HT and Sisal fibers, because they were in mesh form, batches were created with mesh strips with the dimensions of the beam surface. Therefore were separated portions with dimensions of 53mm in width and 2900mm in length.

Figure 4.6 Batches of Curauá fibers of 75 g

Figure 4.7 Sisal fiber

Figure 4.8 Vectran HT fiber

4.1.3 Reinforced Glulam beam

Glued laminated beams were produced by a supplier. According to him, for the assembly were used pieces of Pinus Elliottii glued with two different kind of adhesive polyurethane (PU) and emulsion polymer isocyanate (EPI). The layers were classified visually and by ultrasound for the selection of the pieces with better mechanical properties to be used in the ends. At the end of the assembly the beam width was 53 mm and the height 180 mm.
The bonding of the fiber with the resin to the formation of the fibrous composite was made directly on the Glulam beams. The union of the components occurred in the traction section.

The application of the reinforcement on the beam began with the application of a layer of the adhesive. After applying the first layer, the reinforcing fiber layer was applied. To prevent the formation of air bubbles between adhesive and fiber layer, and to improve the impregnation into the fiber yarns, a pressure was achieved with a roller along the entire reinforcement layer. On the fiber layer was applied a new layer of adhesive so that a total impregnation in the fibers.

Figure 4.9 Application of the reinforcement

In order to protect the reinforcement layer from external agents, an additional wooden layer was added.

Figure 4.10 Reinforcement with Curaua fiber

Figure 4.11 Reinforcement with Sisal fiber

Figure 4.12 Reinforcement with Vectran fiber

4.2 Methods

4.2.1 Bending test

The experimental analysis consisted of preparing and testing 12 laminated timber beams of wood of the species Pinus Elliottii with adhesive PVA, with and without the reinforcement. Each beam has the following dimensions: width of 53 mm, height of 20 ± 0.5 mm each lamina and final height of 180 mm. The beams were evaluated through bending tests, according to the Brazilian timber construction standard NBR 7190:1997.

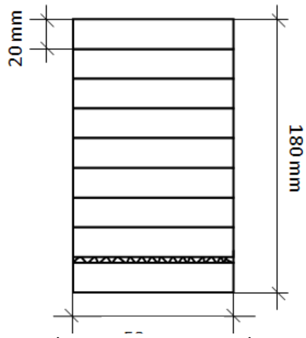

Figure 4.13 Cross section


Figure 4.14 Support of the beam

A static design of a simply supported beam was adopted for the tests, it was performed with the beam supported on a fixed and a movable support with a free span of 2700 mm.

The load was applied in the middle of the span through a hydraulic cylinder and it was monitored by a calibrated load cell. The test was carried out by loading the beam at one point and two points to ensure the pure flexion, so as not to consider the flexural contribution due to the shear stress.


Figure 4.15 Load configuration for a beam in four- point and three-point bending test

In addition, lateral supports were positioned to prevent the lateral rotation of the beam and consequently the loss of stability during the test.

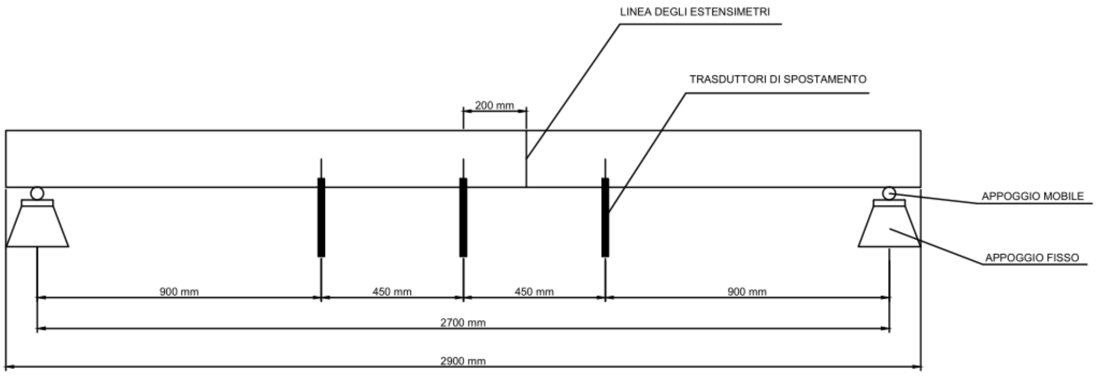

Figure 4.161 Displacement transducers

The vertical displacements of the beams was measured by tree displacement transducers, positioned on the side of the beams near the neutral line. A transducer was positioned in the middle of the span of the beam and the other two arranged symmetrically in the span (45 cm). The values of load and displacements were measured through the load cell and displacement transducers and stored in a computer through a data acquisition system.
On the surface of the beam were placed extensometers in order to allow the monitoring of deformations along the section during the test.

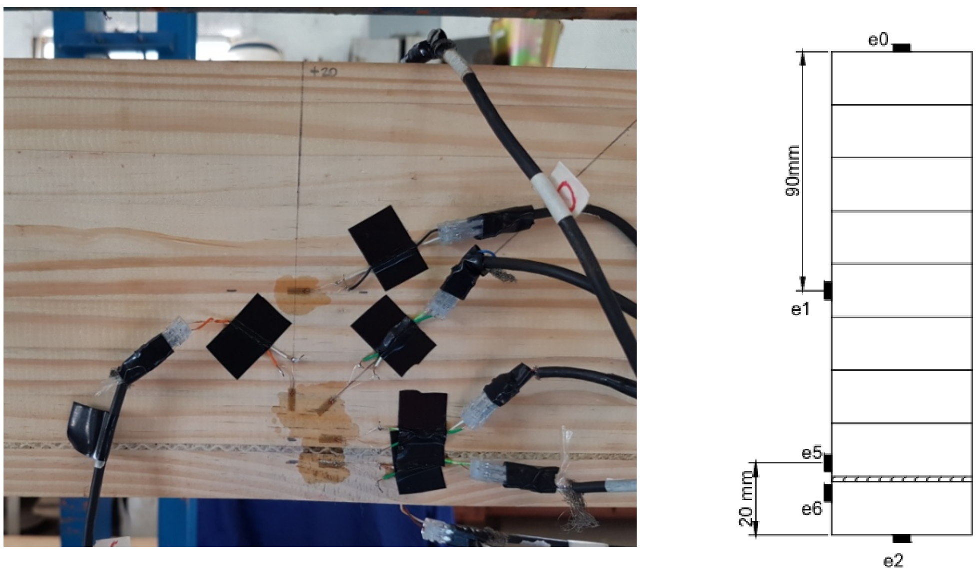

Figure 4.17 Extensometers

Were used seven extensometers, Kyowa type KFG-5-120-C1-5, with 5mm length and 119.8 ± 0.2Ω. The surface of the beam was polished and clean to ensure perfect adhesion of the extensometers. These were positioned as follows: one on the upper surface of the beam, in the compressed area, one on the lower surface, in the traction zone, two more were placed laterally, in the middle and above the fiber, and finally the extensimetric rosette. In addition, the extensometers were vertically aligned and positioned near the middle of the beam but far enough away from the load point to not generate interference in the measurements. Their positioning also takes into account the natural wood defects such as the knots and the direction of the fibers.
The modulus of elasticity in the flexion will be calculated in the elastic regime as Item B.14.2 of the Brazilian standard:

$$E_M = \frac{(F_{50\%} - F_{10\%}) \cdot L^3}{(V_{50\%} - V_{10\%}) \cdot 4 \cdot b \cdot h^3} \qquad [2]$$

F_i: load corresponding to the value i of the load of rupture [N]
i: values corresponding to 10% and 50% of the estimated maximum load
Vi: vertical displacements measured in the middle of the span [mm]
L: length between the supports [mm]
b: width of cross section of beam [mm]
h: height of the cross section of the beam [mm]

As a comparison of stiffness between the types of reinforcements applied, it was calculated the stiffness according to the following form:

$$\overline{EI} = \frac{\Delta F\ L^3}{48\ \Delta V} \qquad [3]$$

EI : global stiffness [Nmm^2]
ΔF: variation of the load in a linear portion of graph load- displacement [N]

ΔV: variation of the displacement in a linear portion of graph load-displacement [mm]

4.2.2 Theoretical analysis: transformed section method

The transformed section method is an alternative procedure for analyzing the bending stresses in a composite beam. A beam made of two or more materials is constructed in such a way that it acts as a single member, as opposed to two or more individual beams each acting with a degree of independence and some interaction. The method consists of transforming the cross section of a composite beam into an equivalent cross section of imaginary beam that is composed of only one material. This new cross section is called the transformed section. Then the imaginary beam with the transformed section is analyzed in the customary manner for a beam of one material.
In the derivation of elementary flexure stress theory we made several assumptions including the assumption that our material is homogeneous and has a constant E value throughout. For many purposes it is not necessary that the material be isotropic, as long as the properties are constant throughout the cross section in the plane of the beam. Even a simple beam composed of two materials which are each homogeneous and isotropic does not satisfy the requirement that the entire beam be homogeneous. Thus elementary theory is not directly applicable.
We construct our hypothetical model by requiring that:

- the dimensions in the loading plane are unaltered,
- the model contains only one material,
- we do not alter the strain distribution,
- the beam carries the same loading with the same deflections, and
- all other assumptions applicable in elementary bending theory have been met (e.g. linear elastic material, initially straight beam, etc.).

The modulus of elasticity E is a measure of stiffness. The transformed section is constructed by replacing one material with the other. Since the transformed section is to carry the same strain distribution and carry the same load as the original section, we must add (or delete) material in such a way that the load carried by the section is unaltered. Thus if we replace a less stiff material (low modulus of elasticity) with a stiffer material (higher modulus of elasticity) we will need less of it by the ratio of the E values. On the other hand, if we replace a high modulus material with a lower modulus material we need more material.

Our transformed section will differ from the actual beam in only a couple of ways. It will be composed of only one material, and the stresses in the altered portion of the cross section will differ by a constant factor from those in the actual section. If the transformed beam is to be equivalent to the original beam, its neutral axis must be located in the same place and its moment-resisting capacity must be the same.

Denoting E_1 and E_2 are the modulus of elasticity for materials 1 and 2, and assume $E_2 > E_1$, the neutral axis of the cross section it obtained from a force equilibrium in x-axis:

$$E_1 \int y \, dA + E_2 \int y \, dA = 0 \qquad [4]$$

In this equation, the integral represent the firsts moments of the two parts of the cross section with respect to the neutral axis. Denote n the modular ratio as:

$$n = \frac{E_1}{E_2} \qquad [5]$$

Then the equilibrium equation can be written:

$$\int y \, dA + \int n\,y \, dA = 0 \qquad [6]$$

The preceding equation show that the neutral axis in unchanged if each element of area dA in material 2 is multiplied by the factor n, provided that the y coordinate for each such element of area is not changed.

Therefore, we can create a new cross section consisting of two parts: area 1 with is dimension unchanged, and area 2 with its width multiply by n. Since the stress in the material is proportional to the modulus of elasticity, multiplying the width of material 2 by n is equivalent to transforming it to material 1. The neutral axis , in the transformed section is in the same position as the neutral axis of the original beam and it is calculated as:

$$y_{cg} = \sum_{i=1}^{n} \left(\frac{n \cdot b \cdot h_i \cdot y_i}{n \cdot b \cdot h_i} \right) \qquad [7]$$

E_i: modulus of elasticity layer i
E_1: modulus of elasticity layer i
h_i: height layer i
b: width
The stiffness is calculated according to the theory of composite cross sections in the linear-elastic state, plastic deformations are not considered.

$$EI = \sum_{i=1}^{n} \left(\frac{E_i \cdot b \cdot h_i{}^3}{12} + E_i \cdot b \cdot h_i \cdot d_i^2 \right) \qquad [8]$$

d_i : distance from C.G. of layer to C.G. of the beam.

The position of the neutral axis and the stiffness are shown in Table 5.1

Fiber	**E_f**	**E_w**	**n**	**b**	**h**	**y_{cg}**	**EI**
-	Mpa	Mpa	-	mm	mm	mm	kNcm²
Curaua'	30000	11889	2,52	52,52	178,62	89,55	3.038.146
Sisal	15200	11889	1,28	52,75	178,69	89,59	3.023.834
Vectran	75000	11889	6,31	52,89	178,84	89,91	3.334.632

Table 4.3 Theoretical calculation

CHAPTER5
RESULTS

The following chapter presents the results of the bending test. Table presents the dimension of the cross-section of each beam, the fiber used as reinforcement and the way of loading.

Beam	Fiber	h_{FIBER} mm	Adhesive	b mm	h mm	Load
VSR1	Beams Without Reinforcement		EPI	52,83	178,78	one point
VSR2			EPI	52,92	178,4	two points
VSR3			EPI	52,68	178,72	one point
CUR1	Curaua'	0,5	PU	52,6	178,35	one and two points
CUR2			EPI	52,37	178,92	
CUR3			EPI	52	178,58	one point
SIS1	Sisal	0,5	PU	52,78	178,82	one and two points
SIS2			EPI	52,68	178,5	
SIS3			EPI	52,78	178,75	one point
VEC1	Vectran	1	PU	52,85	179,1	one and two points
VEC2			EPI	52,85	178,67	
VEC3			EPI	52,97	178,75	one point

Table 5.1 Beams information

5.1 Load- deflection behaviour

The following load-displacement curves define the displacement in the middle as a function of the increase in the load. However, the displacement measurement has not been carried out until the maximum load, but to approximately half.

The bending modulus of elasticity (MOE) of the no reinforcement beams is calculated from date taken from the linear region of the load-deflection curve.

Beams without reinforcement

BEAM	Breaking Load N	E Gpa	E_M Gpa
VSR1	-	10,7	9.87
VSR3	21.356,37	9,05	

Table 5.2 Breaking load and MOE_ Beams without reinforcement

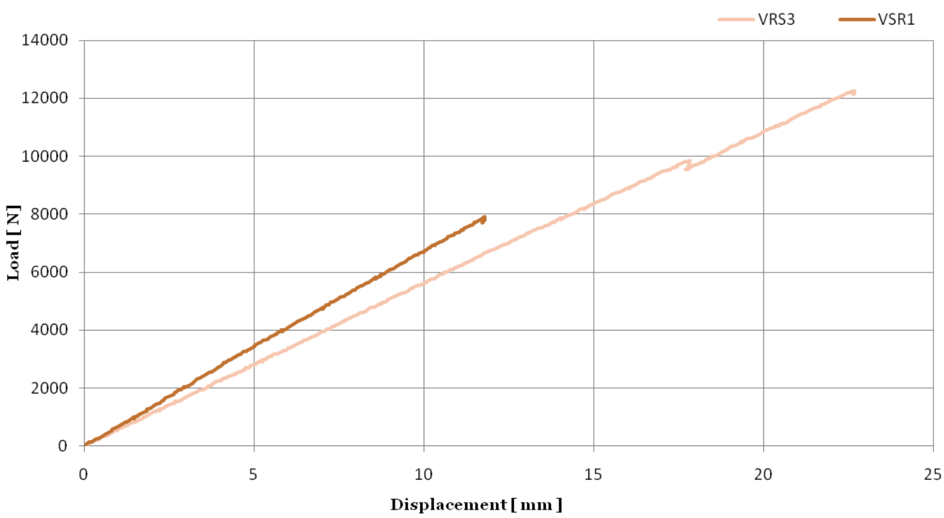

Figure 5.1 Load-deflection curves_Beams without reinforcement

Beams with reinforcement of Curaua'

BEAM	Breaking Load N
CUR 1	16.314,03
CUR 2	22.376,61
CUR 3	13.321,98

Table 5.3 Breaking load _ Beams with reinforcement of Curauà

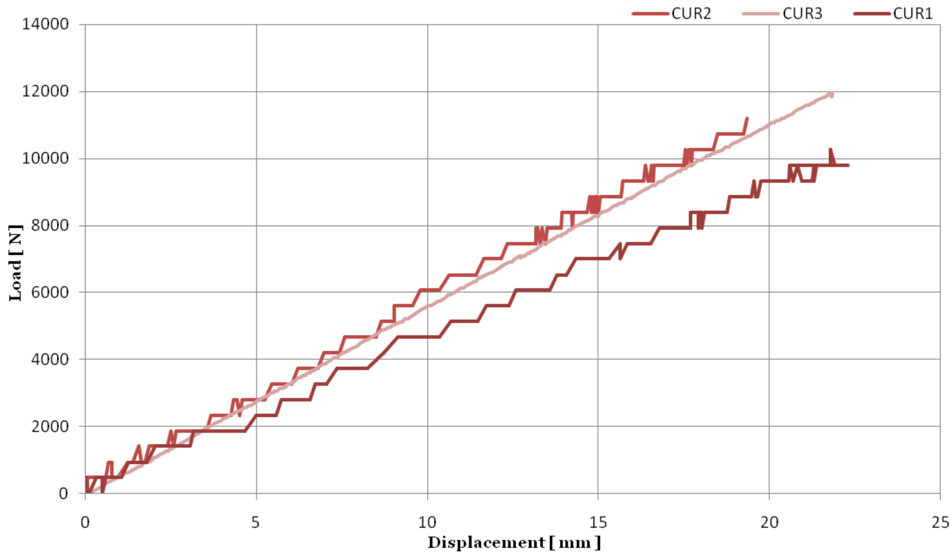

Figure 5.2 Load-deflection curves_Beams with reinforcement of Curauà

Beams with reinforcement of Sisal

BEAM	Breaking Load N
SIS1	20.512,71
SIS2	20.051,64
SIS3	19.835,82

Table 5.4 Breaking load _ Beams with reinforcement of Sisal

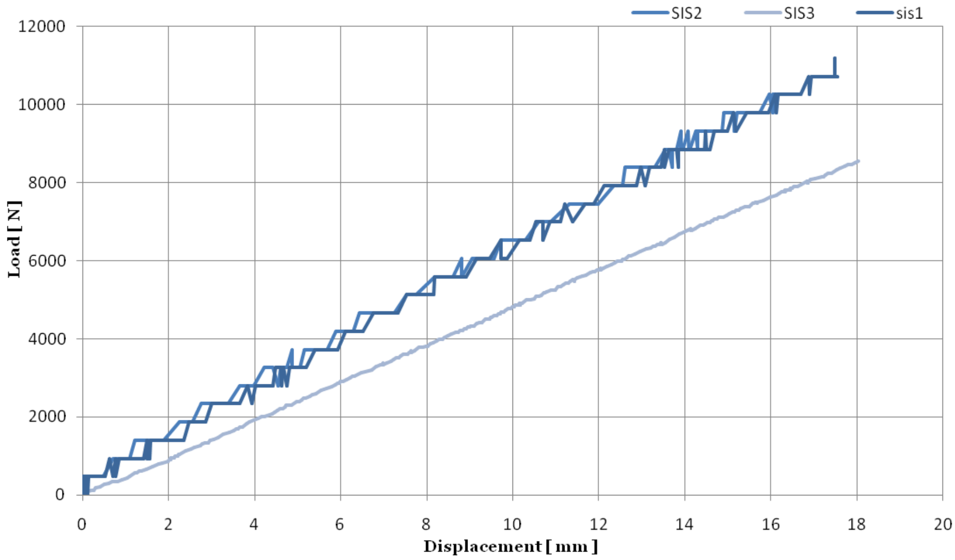

Figure 5.3 Load-deflection curves_Beams with reinforcement of Sisal

Beams with reinforcement of Vectran

BEAM	Breaking Load N
VEC1	20.051,64
VEC2	18.648,81
VEC3	21.091,5

Table 5.5 Breaking load _ Beams with reinforcement of Vectran

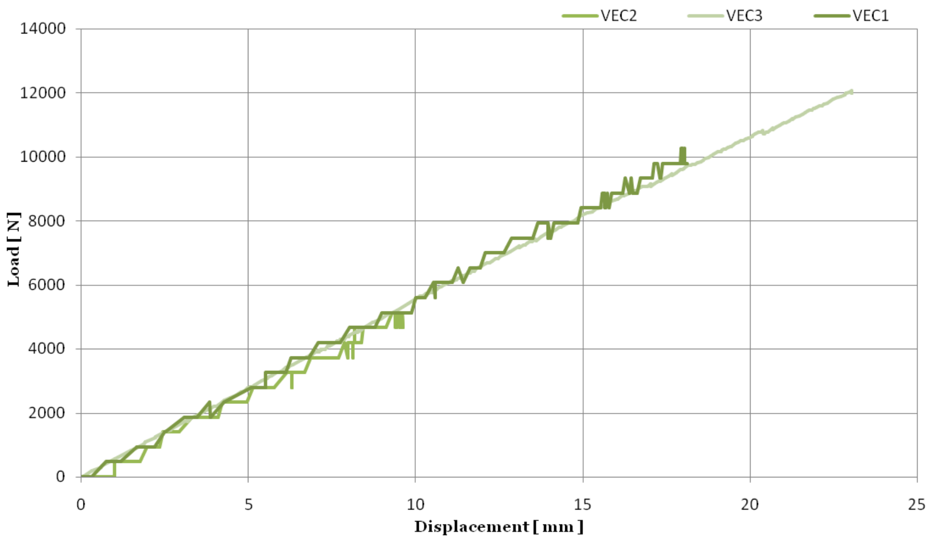

Figure 5.4 Load-deflection curves_Beams with reinforcement of Vectran

5.2 Deflection

The following diagrams show the displacement profile along the beam for different load values.

Excessive deflection of a beam not only is visually disturbing but also may cause damage to other parts of the building. For this reason, the Brazilian Code limit the maximum deflection of a beam to about 1/300 of its spans.

Beams with reinforcement of Curaua'

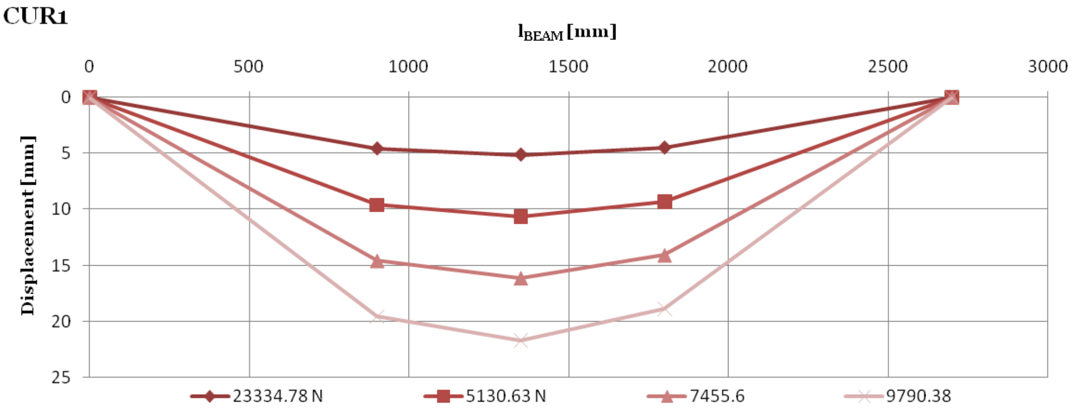

Figure 5.5 Deflection profile_CUR1

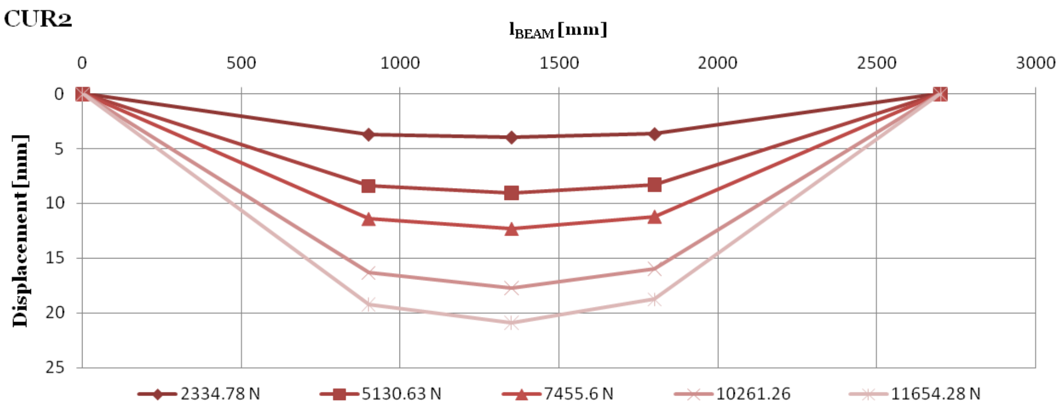

Figure 5.6 Deflection profile_CUR2

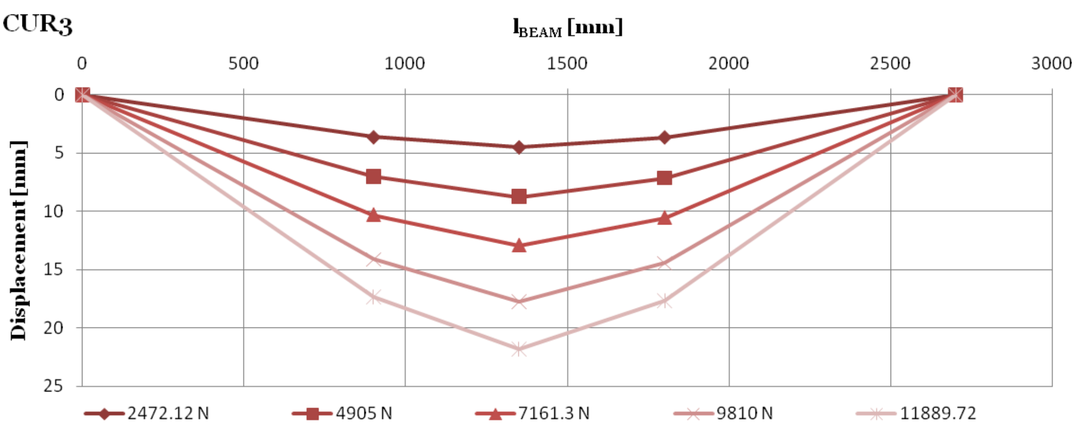

Figure 5.7 Deflection profile_CUR3

Beams with reinforcement of Sisal

SIS1

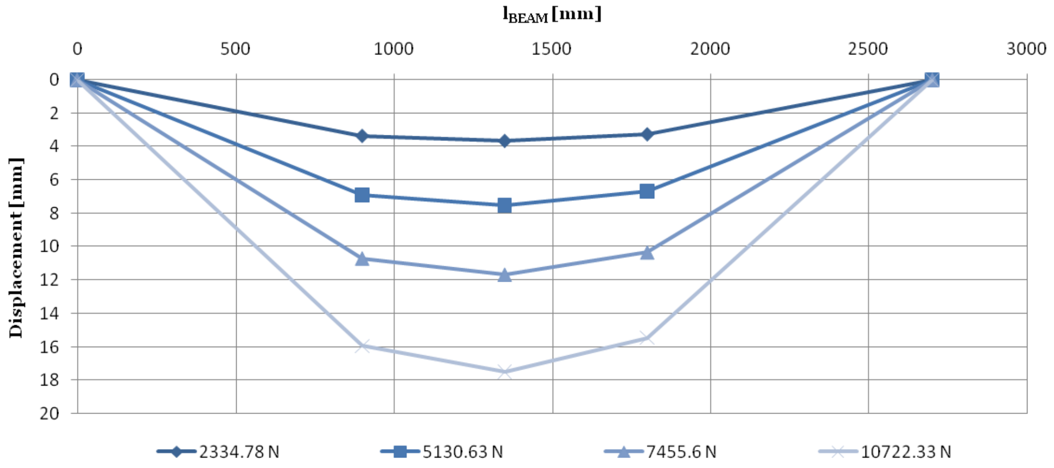

Figure 5.8 Deflection profile_SIS1

SIS2

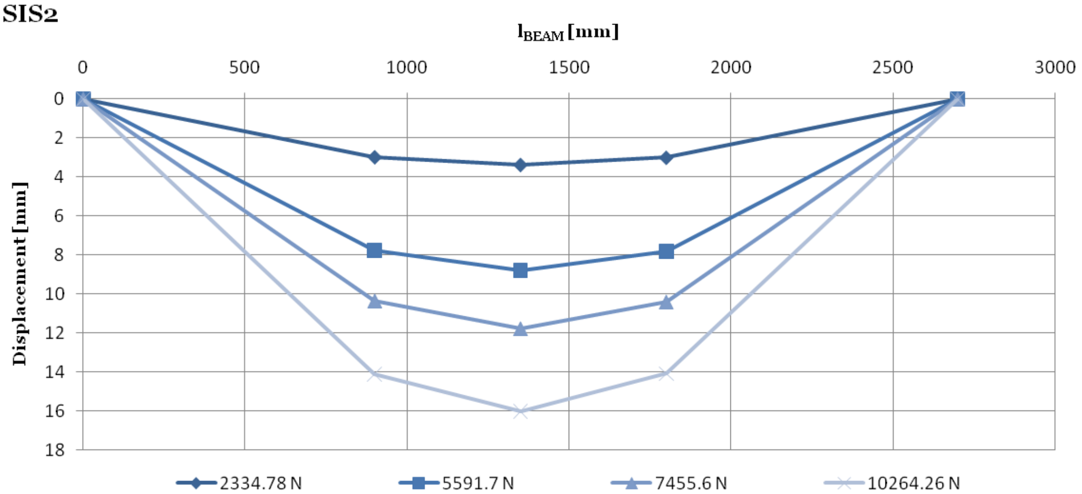

Figure 5.9 Deflection profile_SIS2

SIS3

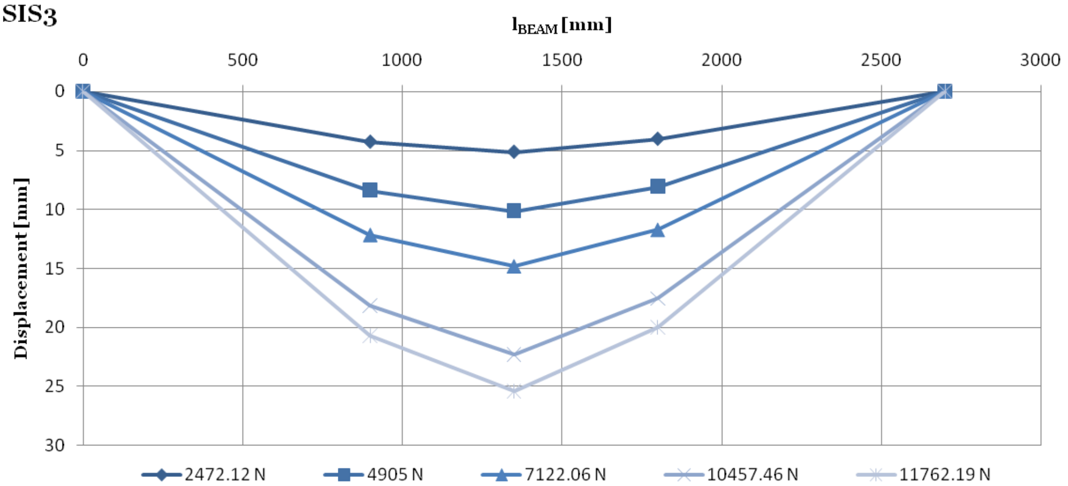

Figure 5.10 Deflection profile_SIS3

Beams with reinforcement of Vectran

VEC1

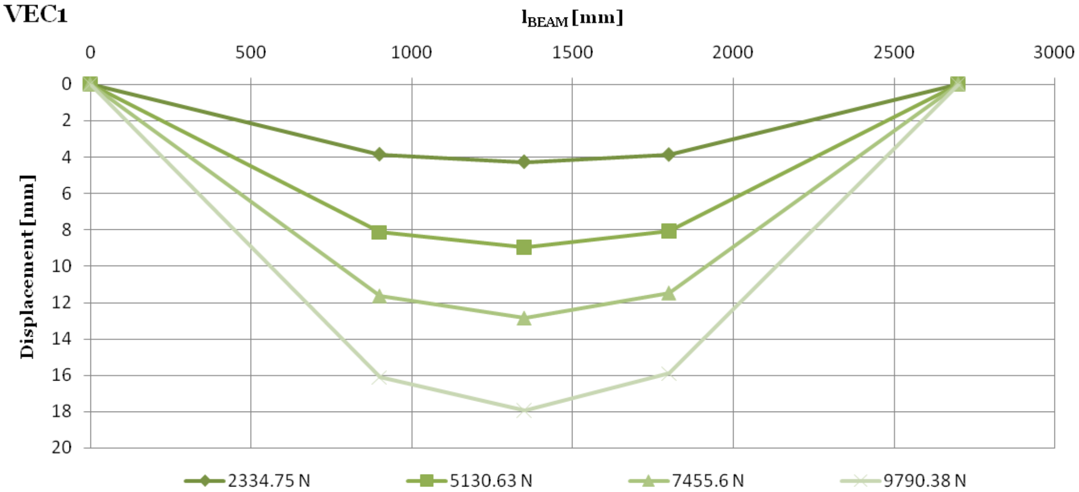

Figure 5.11 Deflection profile_VEC1

VEC2

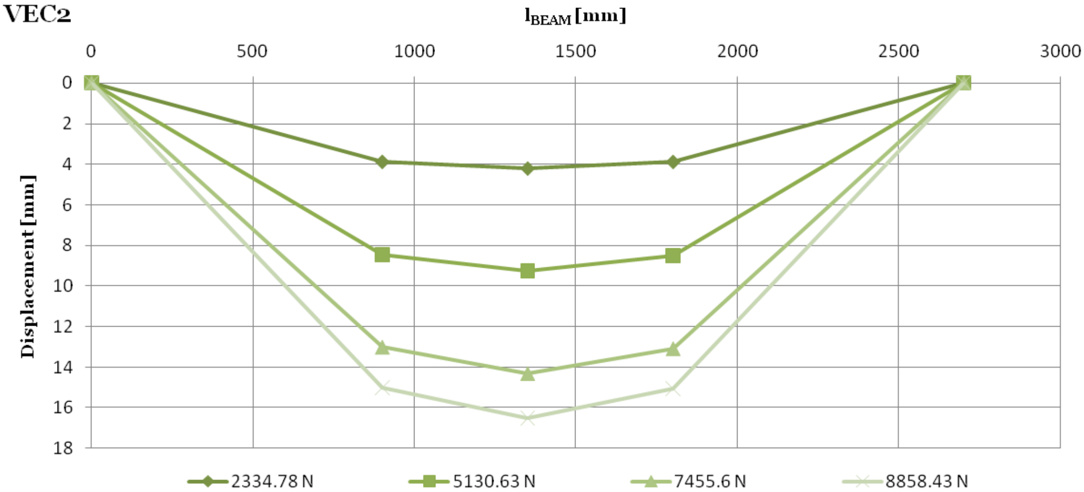

Figure 5.12 Deflection profile_VEC2

VEC3

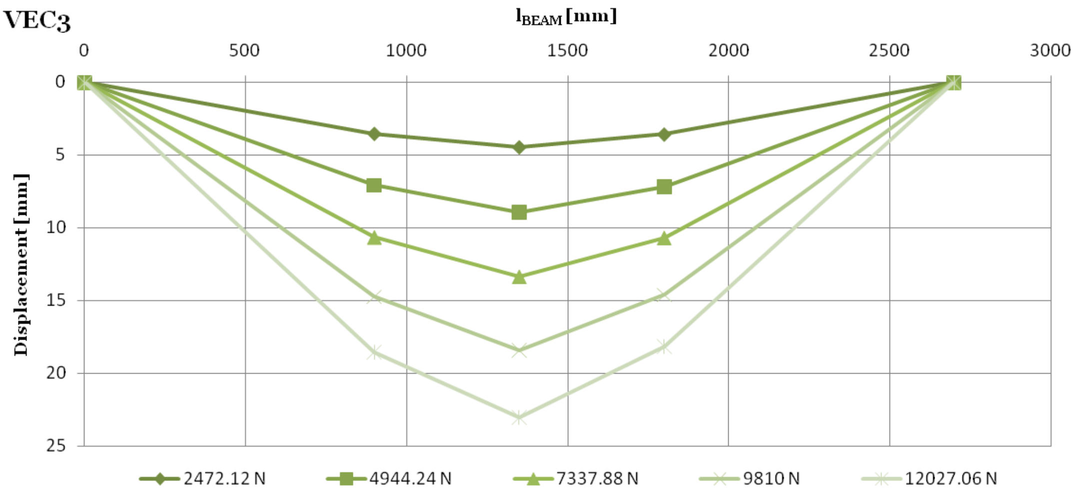

Figure 5.13 Deflection profile_VEC3

5.3 Stress- strain curves

Four regions of the stress- strain curve for wood composites can be identified:
a. Initial alignment
b. Linear elastic
c. Curvilinear
d. Post failure.

The first region is caused by specimen misalignment in the testing apparatus and surface roughness. It is a transient occurrence, and after a modest load increase surface roughness is suppressed and linear strain behaviour follows. The region of initial alignment is ignored in the analysis of the data. A maximum tangent line can be fitted to the second region which is that of assumed linearity between stress and strain to which Hooke's law applies. The point where the curve deviates from a straight line is termed the proportional limit since, beyond this point, stress is no longer proportional to strain. Beyond the proportional limit, strain increases at a faster rate than stress to produce a region of convex curvilinearity. The upper limit of this region is the ultimate stress that the material can sustain. This point is point is particularly important in the use of wood composites. Unfortunately, however, it is not a constant, but it can be influenced by such factors as temperature, moisture, and rate o duration of loading. The post- failure region may be of great significance in some applications. It indicates whether full or partial failure has occurred. Members of structure which have failed partially are still capable of supporting load and can play a significant role in structural safety.

Because compression can be considered as a negative tension, the stress-strain curves for both are represented as a single curve. In order to establish failure criteria the stress-strain relationship of the material is analyzed.

Beams with reinforcement of Curaua'

CUR1

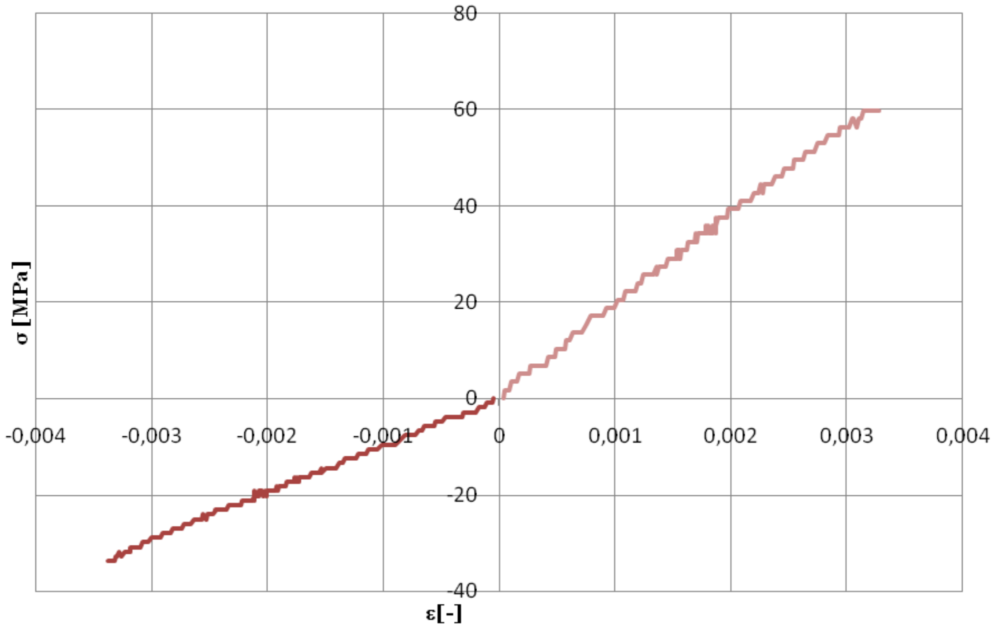

Figure 5.14 Stress-strain_CUR1

CUR2

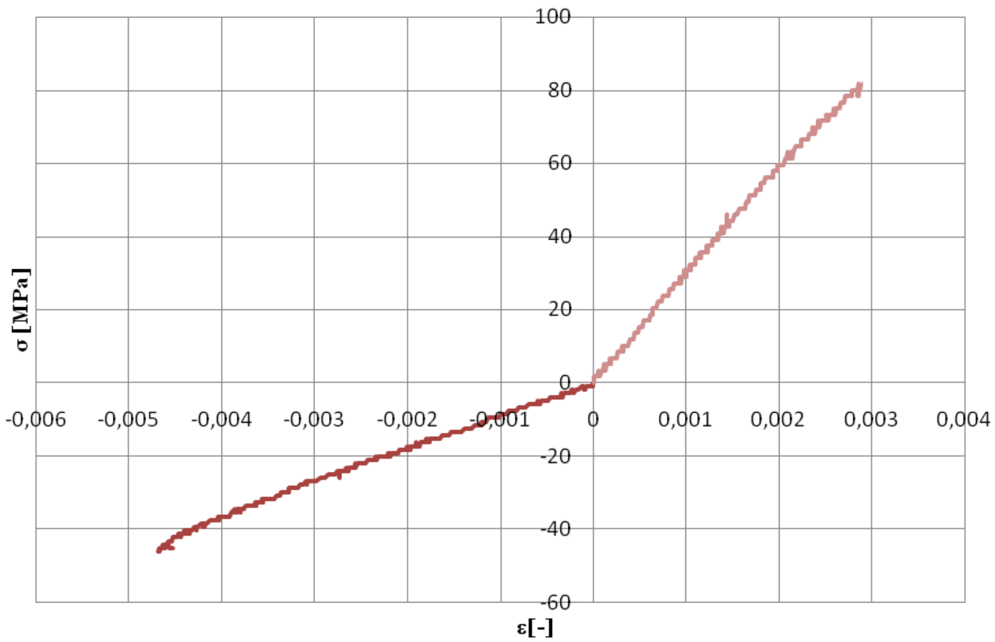

Figure 5.15 Stress-strain_CUR2

CUR3

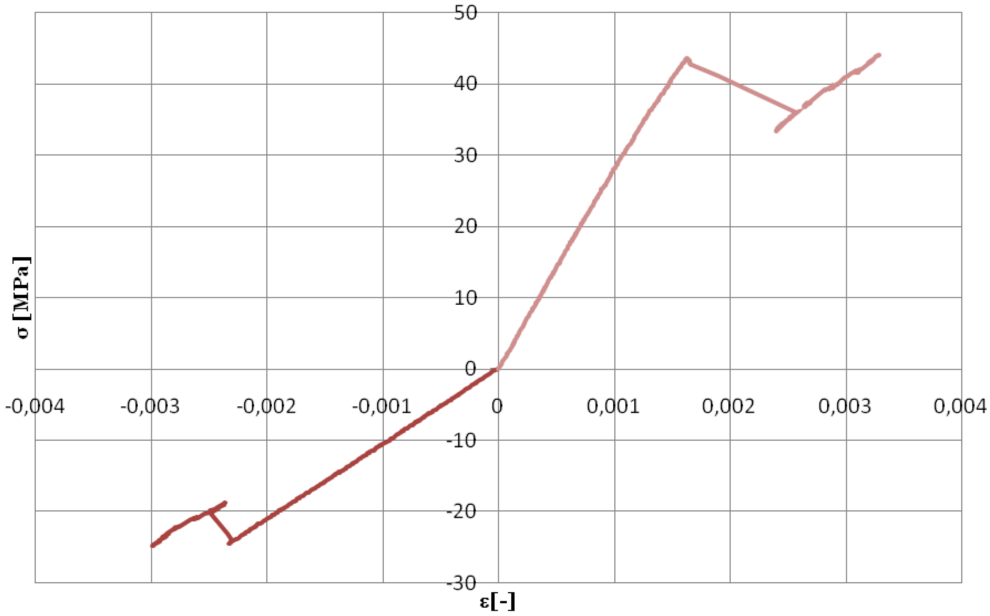

Figure 5.16 Stress-strain_CUR3

Beams with reinforcement of Sisal

SIS1

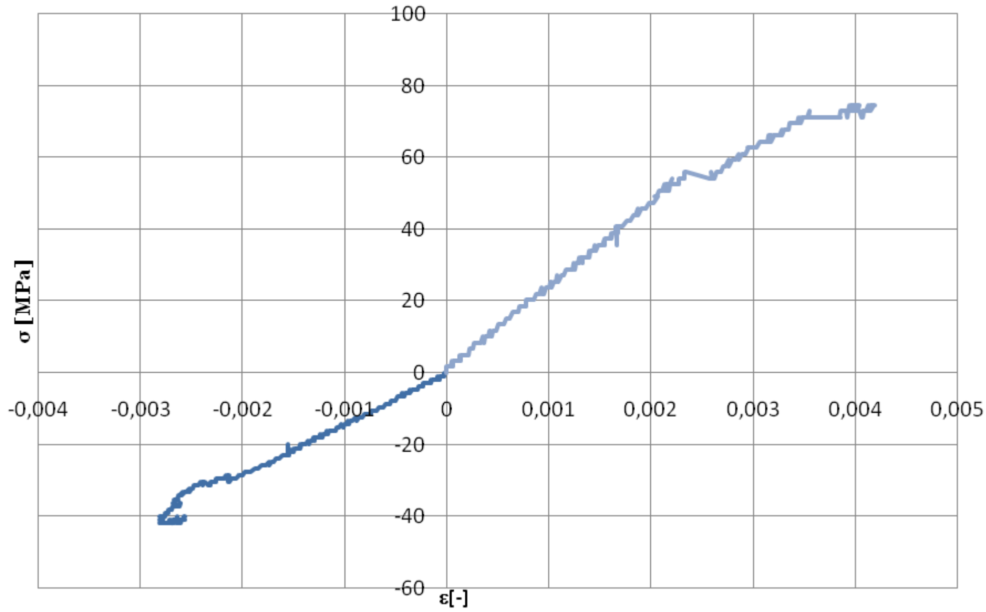

Figure 5.17 Stress-strain_SIS1

SIS2

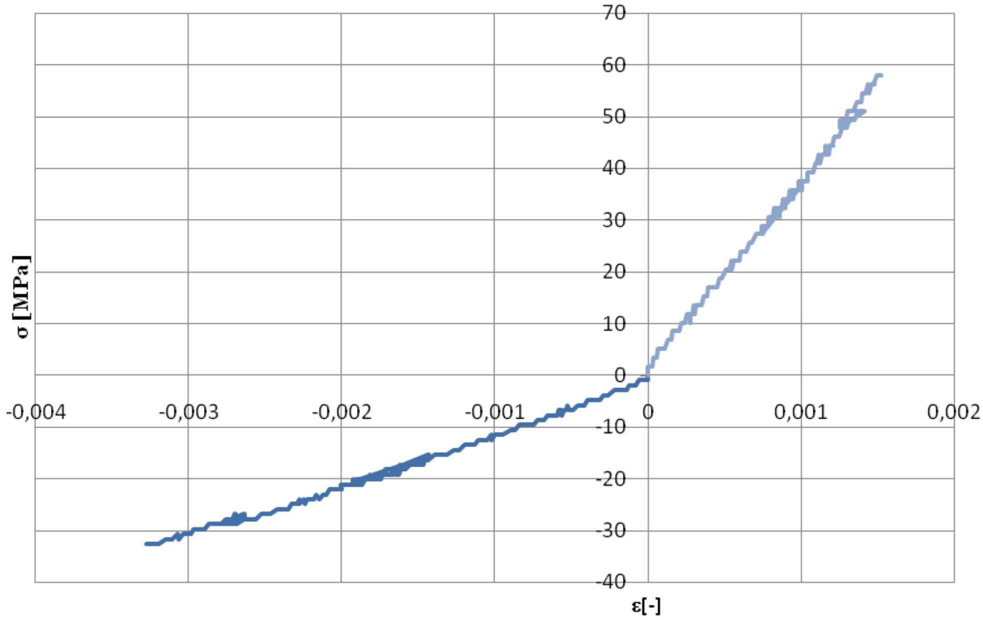

Figure 5.18 Stress-strain_SIS2

SIS3

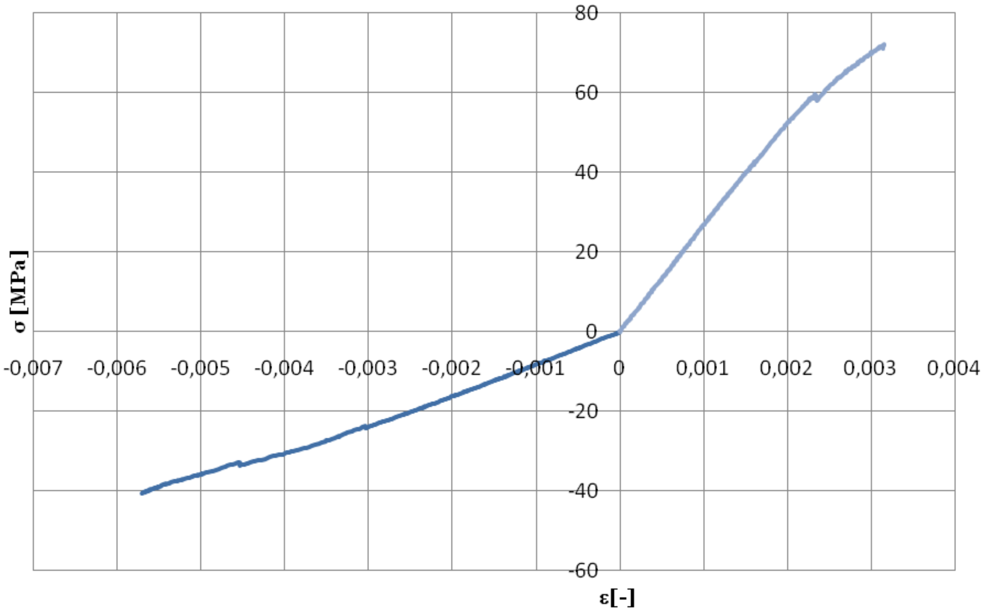

Figure 5.19 Stress-strain_SIS3

Beams with reinforcement of Vectran

VEC1

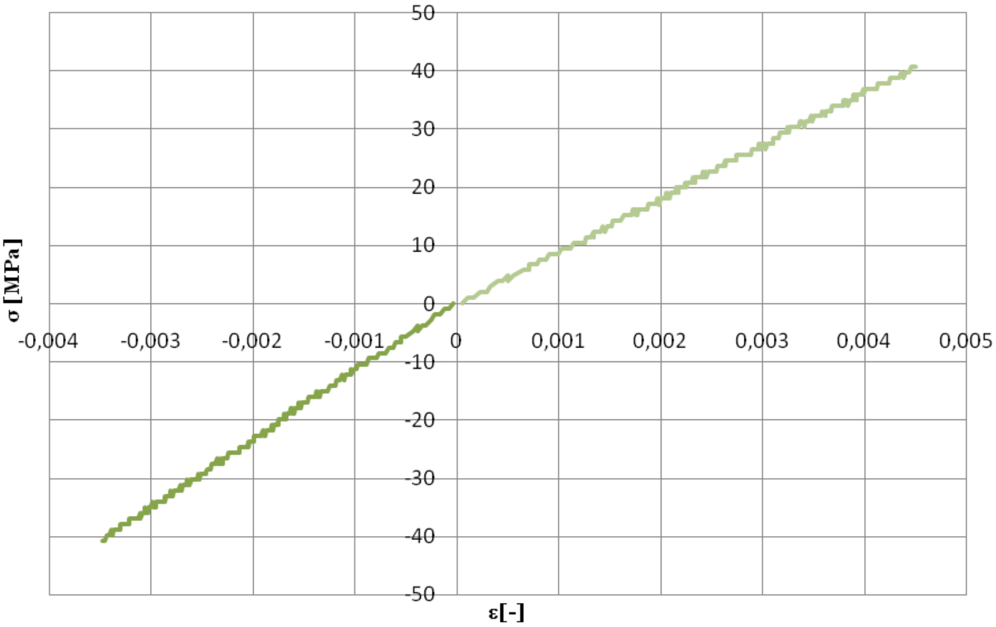

Figure 5.20 Stress-strain_VEC1

VEC2

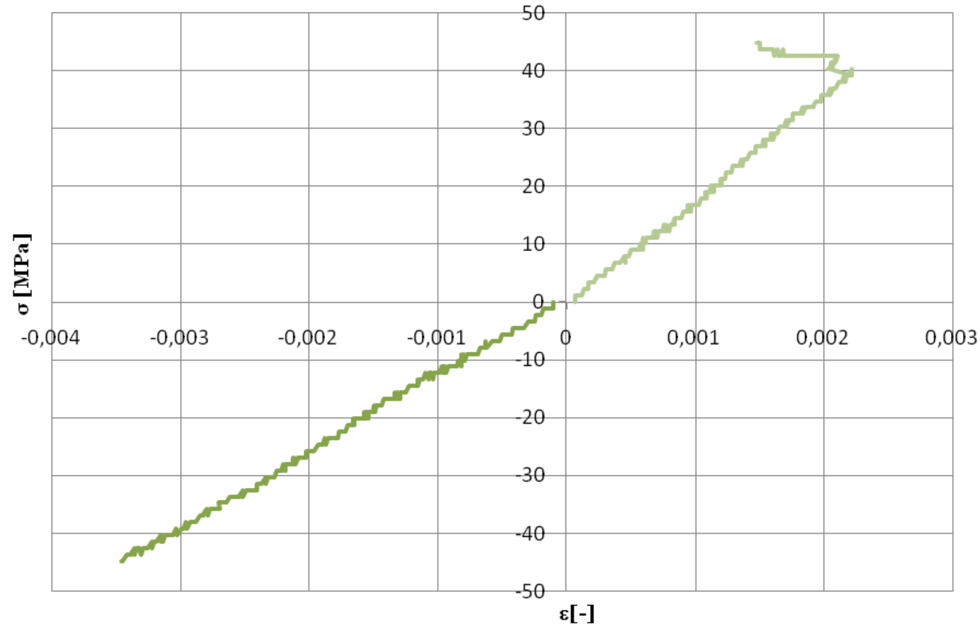

Figure 5.21 Stress-strain_VEC2

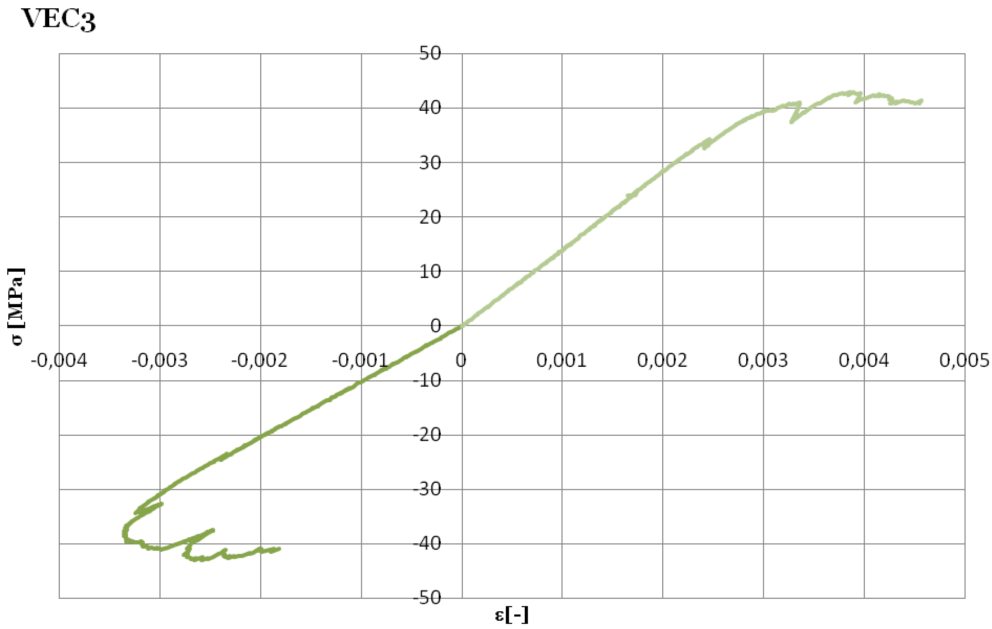

Figure 5.22 Stress-strain_VEC3

5.4 Moment- curvature

Bending deflections are dependent on the moment-curvature relationship. Moment curvature analysis is a method to accurately determine the load-deformation behaviour of a section using nonlinear material stress- strain relationships. For a given axial load there exist an extreme compression fiber strain and a section curvature at which the nonlinear stress distribution is in equilibrium with the applied axial load. A unique bending moment can be calculated at this section curvature from stress distribution. The extreme compression strain and section curvature can be iterated until a range of moment-curvature values are obtained.

Beams with reinforcement of Curaua'

BEAM	μ_{max} 1/m	Maximum Bending Moment Nm
CUR1	0,042	9.380,56
CUR2	0,048	12.866,55
CUR3	0,025	6.864,79

Table 5.6 Maximum bending moment and curvature_ Beams with reinforcement of Curaua'

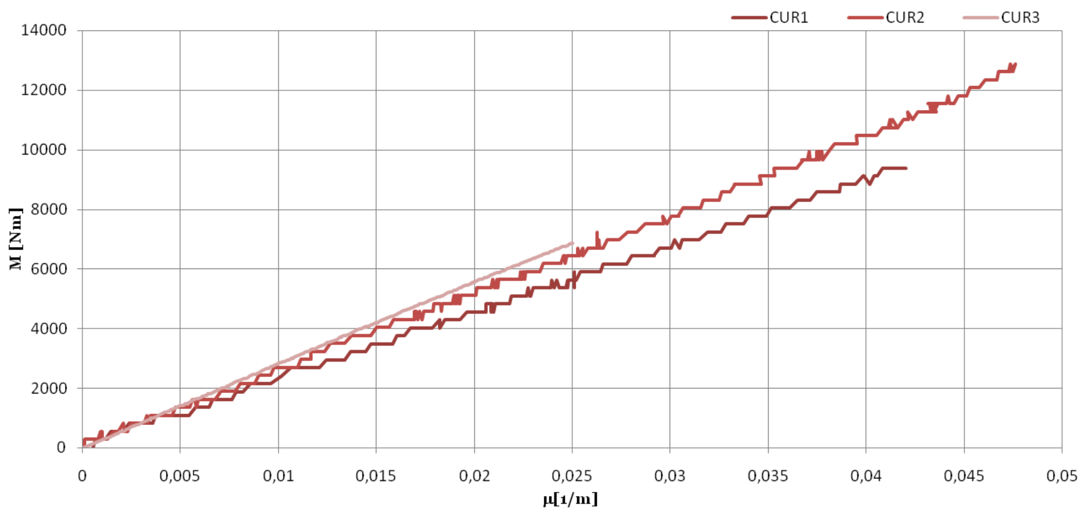

Figure 5.23 Moment- curvature curves_ Beams with reinforcement of Curaua'

BEAM	EI_{TAN} [kNcm²]	EI_{SEC} [kNcm²]	Index of deformation EI_{TAN}/EI_{SEC}
CUR1	2.280.178,45	2.232.360,72	1,021
CUR2	2.747.248,62	2.703.268,44	1,016
CUR3	2.812.307,53	2.746.263,46	1,024

Table 5.7 Tangent and secant stiffness_ Beams with reinforcement of Curaua'

Beams with reinforcement of Sisal

BEAM	μ_{max} 1/m	Maximum Bending Moment Nm
SIS1	0,043	11794.8
SIS2	0,041	11529.69
SIS3	0,056	11405.59

Table 5.8 Maximum bending moment and curvature_ Beams with reinforcement of Sisal

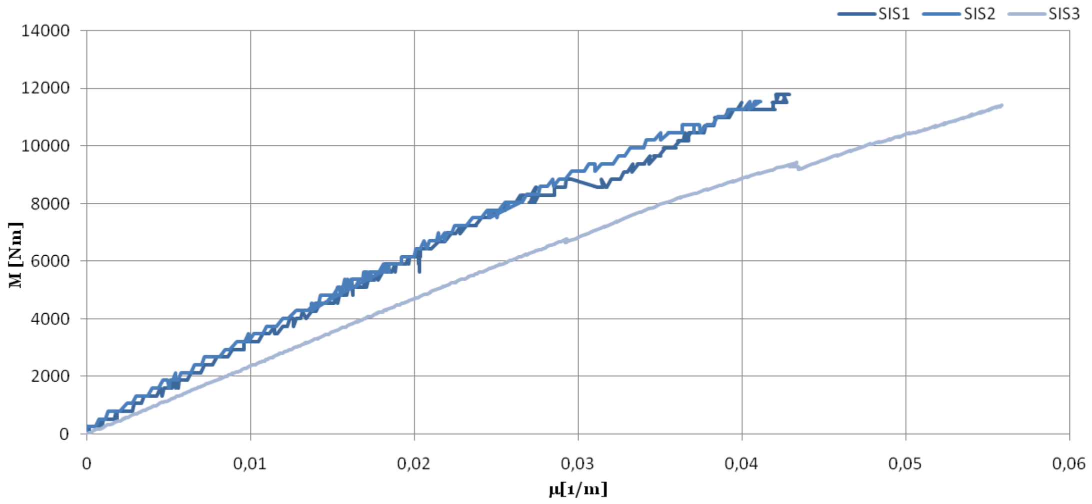

Figure 5.24 Moment- curvature curves_ Beams with reinforcement of Sisal

BEAM	EI_{TAN} [kNcm²]	EI_{SEC} [kNcm²]	Index of deformation EI_{TAN}/EI_{SEC}
SIS1	3.049.143,19	2.751.140,32	1,108
SIS2	3.030.199,54	2.804.137,40	1,081
SIS3	2.328.850,77	2.042.113,01	1,140

Table 5.9 Tangent and secant stiffness_ Beams with reinforcement of Sisal

Beams with reinforcement of Vectran

BEAM	μ_{max} 1/m	Maximum Bending Moment Nm
VEC1	0,039	11529.69
VEC2	0,036	10457.95
VEC3	0,041	12054.28

Table 5.10 Maximum bending moment and curvature_ Beams with reinforcement of Vectran

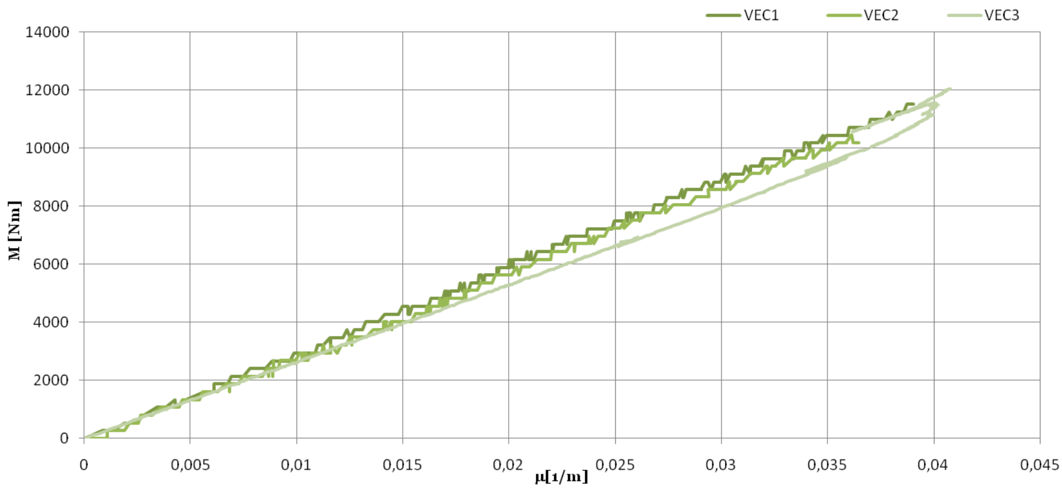

Figure 5.25 Moment- curvature curves_ Beams with reinforcement of Vectran

BEAM	EI_{TAN} [kNcm²]	EI_{SEC} [kNcm²]	Index of deformation EI_{TAN}/EI_{SEC}
VEC1	3.010.263,18	2.953.762,06	1,019
VEC2	2.905.344,48	2.866.266,49	1,014
VEC3	2.959.420,08	2.956.338,01	1,001

Table 5.11 Tangent and secant stiffness_ Beams with reinforcement of Vectran

CHAPTER 6
ANALYSIS OF RESULTS

6.1 Ultimate load carrying capacity

The difference between the lowest and highest loads shows the large variability in the strength properties of a timber. Since timber is a natural material these results are expected and in design they are addressed by using appropriate safety factors. If it's possible reduce this large variability, there is potential to make a design of timber less conservative in the future. The results show a large variability of value of breaking load in the beams reinforced with Curaua' fiber, this may be due to the fact that this kind of fiber doesn't appear in form of mesh therefore it is less controllable. Instead the beams reinforced with Sisal and Vectran fiber present similar values of breaking load, this suggests a reduction in variability of the ultimate load capacity of beams that makes the material can be monitored.

Beam	Breaking load [N]
Curauà	17.337,54
Sisal	20.133,39
Vectran	19.930,65

Table 6.1 Breaking load

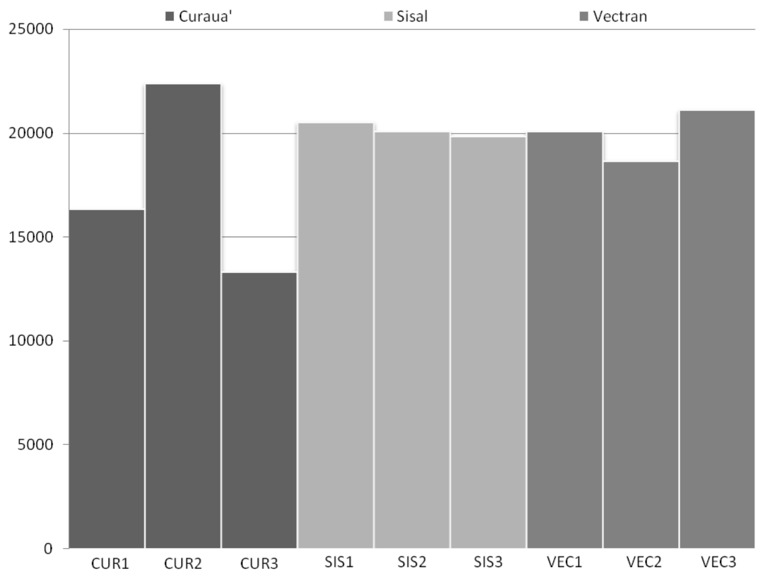

Figure 6.1 Breaking load [N]

6.2 Failure

Failure must be considered one of the most significant mechanical properties. Much of materials engineering is based on establishing economic design without failure. The absence of failure is a necessity of safety as well as for other fundamental considerations.

Bending results in longitudinal tension and compression stresses distributed over the depth of the cross section. The unreinforced beam failed within the elastic region due to a tension failure of the bottom laminations. Splintering tension occurs as shown in Figure 6.2, this failure consists of a considerable number of slight tension failures, producing a ragged or splintery break on the under surface of the beam. Because of the timber's brittle nature when exposed to tension, the beam failed catastrophically without visible failures before reaching ultimate load.

Experimental test carried out on reinforced beams demonstrated that the most frequent failure mechanism is the one in which tension failure occurs, with or without partial plasticization of the compression zone. The adhesion between timber and composite material failed only after timber rupture. Two types of failure mechanisms prevailed for the beams: the timber fracture at the end of the bonded reinforced composites and timber longitudinal splitting. Compressive failure was observed in one of the specimens (Figure 6.11).

The glulam beams reinforced with Sisal especially revealed more ductile behaviour when compared to the others beams. The amount of ductile behaviour in the reinforced beams mostly depends on the quality of the bottom timber laminations. The FRP composites act like bridges over the timber defects and make the structural member section more ductile.

Figure 6.2 Failure_VSR1

Figure 6.3 Failure_CUR1

Figure 6.4 Failure_CUR2

Figure 6.5 Failure_CUR3

Figure 6.6 Failure_SIS1

Figure 6.7 Failure_SIS2

Figure 6.8 Failure_SIS3

Figure 6.9 Failure_VEC1

Figure 6.10 Failure_VEC2

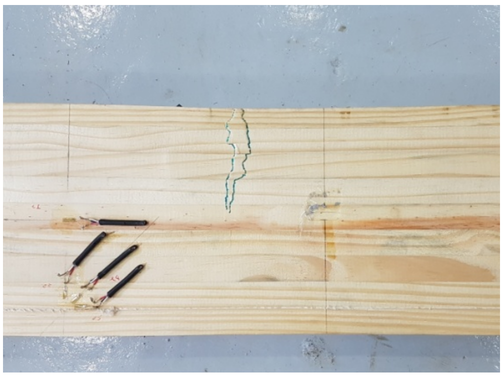

Figure 6.11 Failure_VEC3

6.3 Moment- curvature analysis

For moment- curvature curves shown in Figures, the elastic region up to half the failure load was considered to determine the tangent stiffness for each beam.
Instead, the secant stiffness was calculated as the ratio between the maximum bending moment and the maximum curvature.
By reinforcement elements in a tense area, the strength of the beams can be increased beacuse reinforcement elements start work when the elastic compression linearity limit is exceeded. From this moment on, the compressed wood starts to plasticize, the deformations increase and the neutral axis moves toward the tense edge, causing the tensile stress increase.
When the reinforcement did not work, exceeding the maximum tensile strength limit could cause the brittle fracture; with the reinforcement, instead, it is possible to use the plastic compression reserve of the material.
The curves of the beams reinforced with Curaua and Vectran fibers are linear to the crisis that indicating a brittle fracture in the tense area. Sisal fiber reinforced beams, on the other hand, show a curve initially linear and subsequently slightly descending. Breaking occurs always in a tense area but with greater ductility, due to the plasticization of the section.

Beam	μ_{max} **[1/m]**	**Bending Moment_max [Nm]**	EI_{SEC} **[kNcm²]**	EI_{TAN} **[kNcm²]**	**Index of deformation** EI_{TAN}/EI_{SEC}
Curauà	0,038	9.703,97	2.560.630,87	2.613.244,86	1,021
Sisal	0,047	11.576,69	2.532.463,57	2.802.731,16	1,11
Vectran	0,039	11.371,75	2.925.354,73	2.958.342,58	1,011

Table 6.2 Moment- curvature analysis

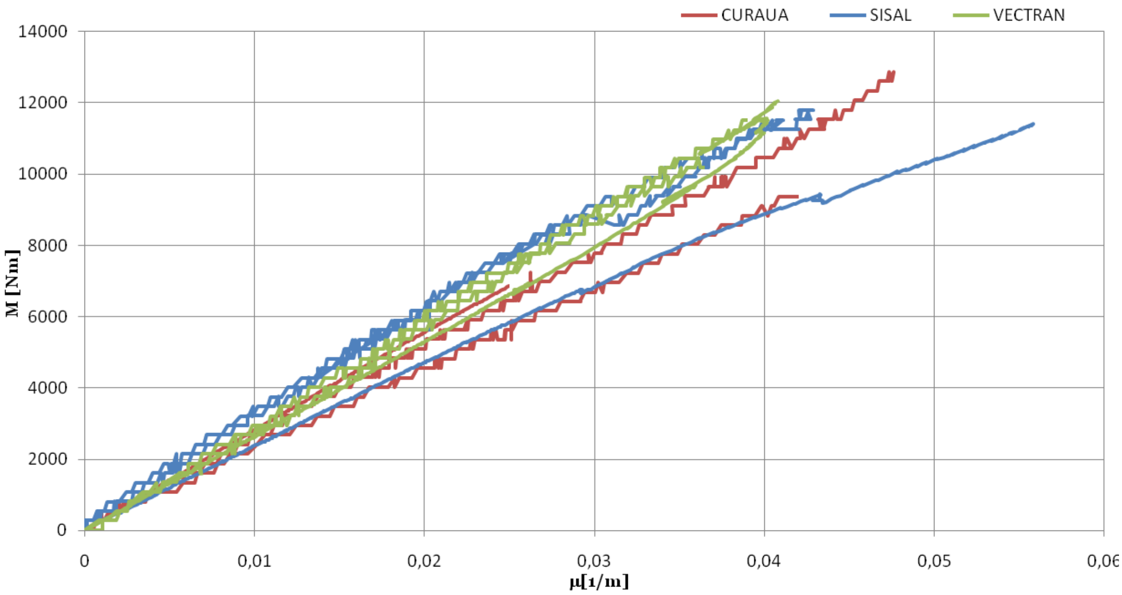

Figure 6.12 Moment- curvature analysis

6.4 Strain distribution

For each beams, the strain was monitorated and the strain profiles of unreinforced and reinforced beams are shown at different load levels in Figure. These profiles report compressive and tensile strains as negative and positive values at the x-axis, respectively, and the strain gauge locations at the y-axis corresponding to the compression and tension zone of the cross section.

The tensile and compressive strain were symmetric for the unreinforced beams. The strain distribution across the section was quite linear until failure, confirming the theory that plane sections remain plane during bending.

Linear distribution over the specimen depth could be observed in the elastic range for reinforced beams. A non-linear strain distribution nearby the state of failure could be observed in reinforced beams where plastic behaviour in the compression zone was reached. For reinforced with Sisal fiber , the non linear behaviour of compressed wood occurs in all of the beams.

The tensile stress distribution across the section were calculated at a load level just before the maximum load, using date obtained from strain gauges and values of elasticity modulus found in the literature, of the fibers od Curaua', Sisal and Vectran.

Beams without reinforcement

VSR1

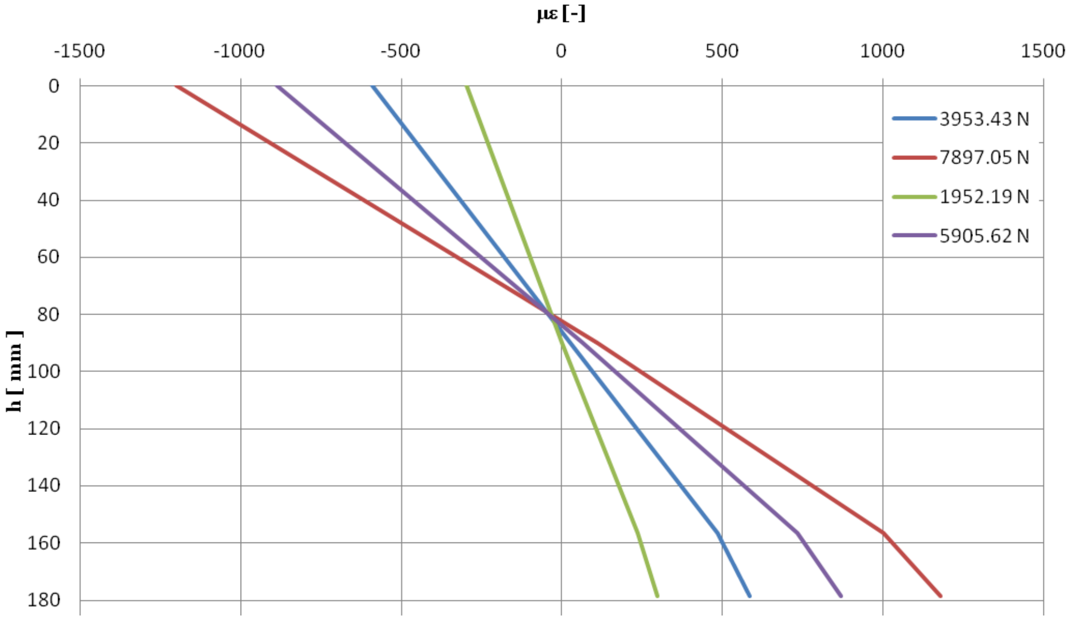

Figure 6.13 Strain distribution_VRS1

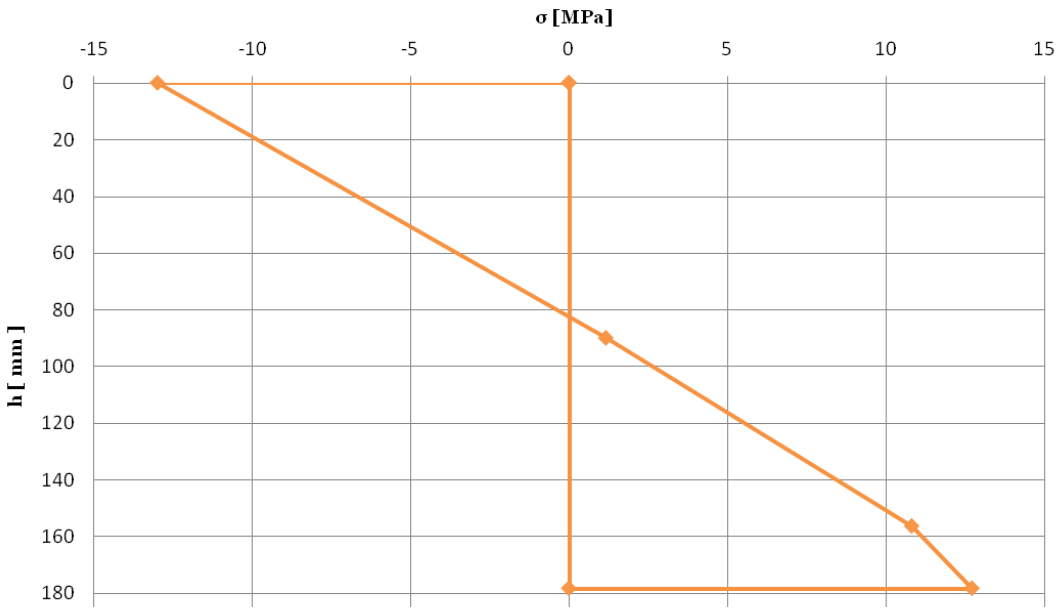

Figure 6.14 Stress distribution_F=7897,05 N_VSR1

Beams with reinforcement of Curaua'

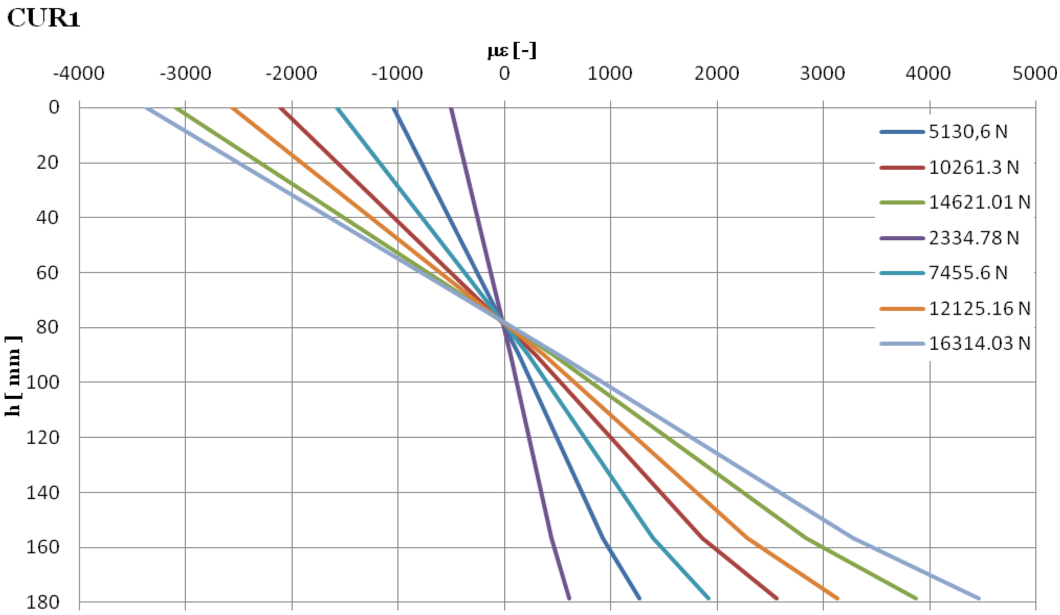

Figure 6.15 Strain distribution_CUR1

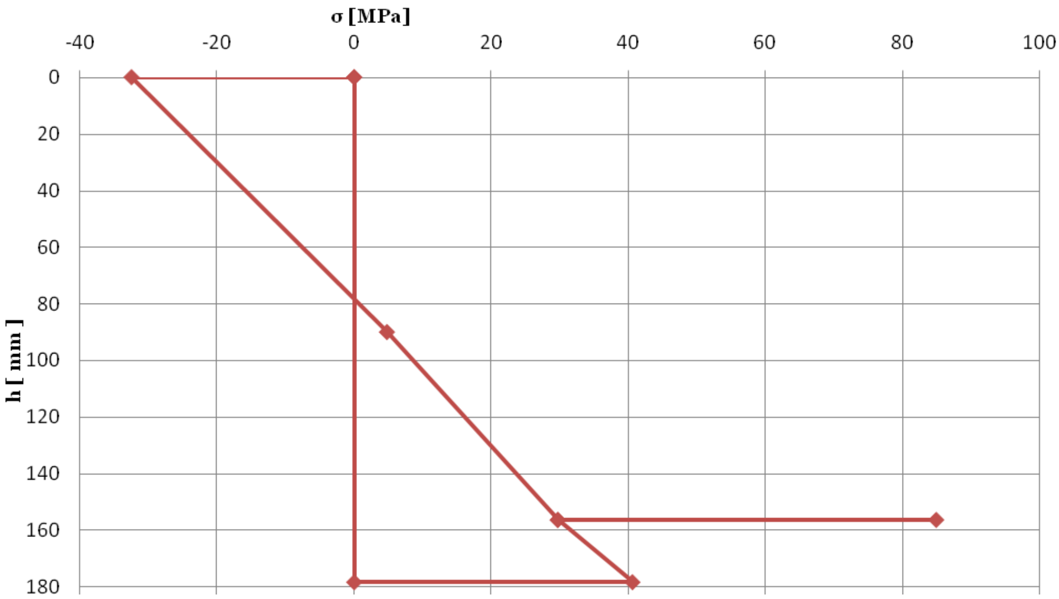

Figure 6.16 Stress distribution_ F=14921,01 N _CUR1

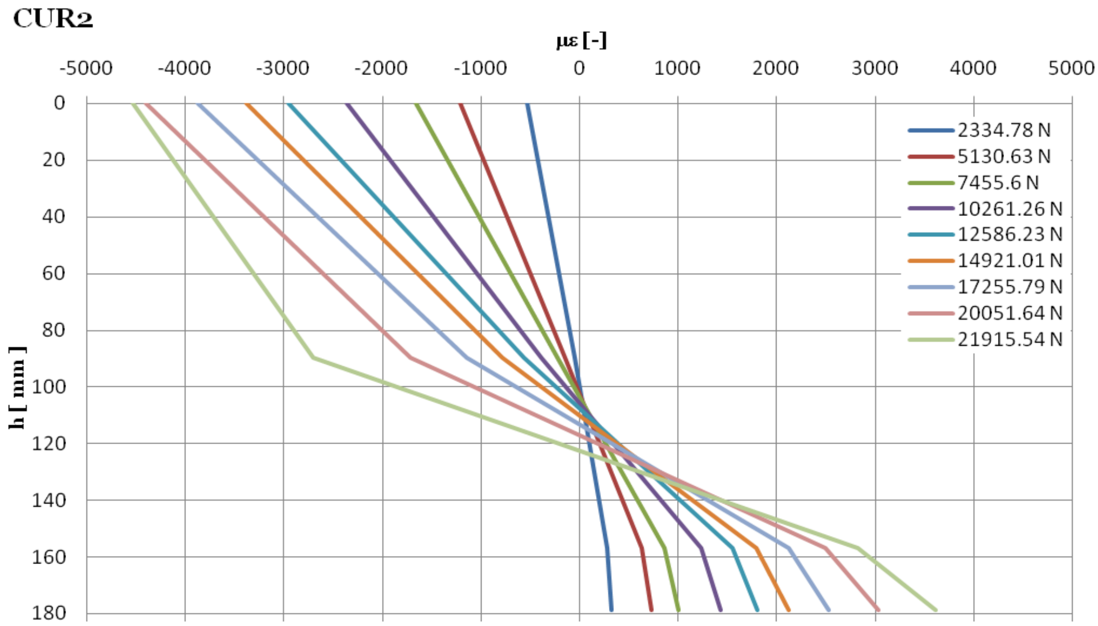

Figure 6.17 Strain distribution_CUR2

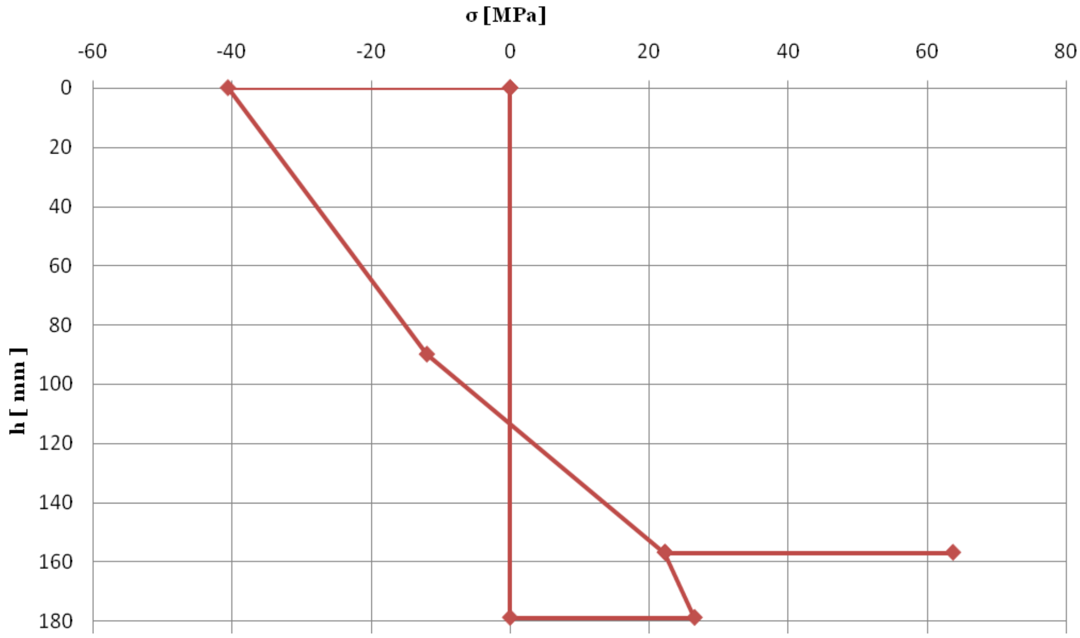

Figure 6.18 Stress distribution_ F=17255,79 N _CUR2

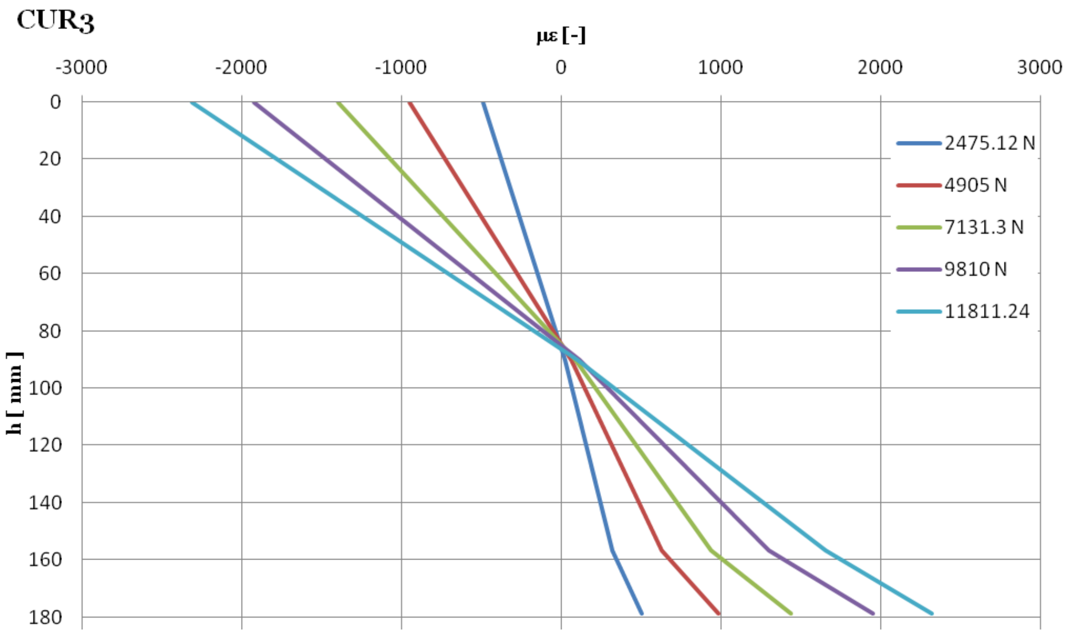

Figure 6.19 Strain distribution_CUR3

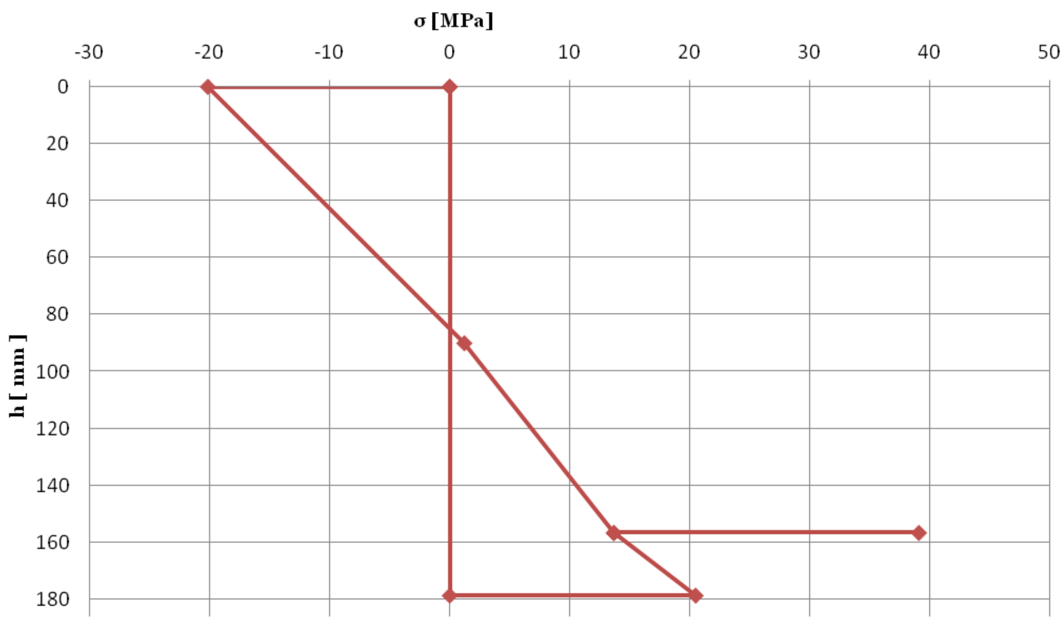

Figure 6.19 Stress distribution_ F=9810 N_CUR3

Beams with reinforcement of Sisal

SIS1

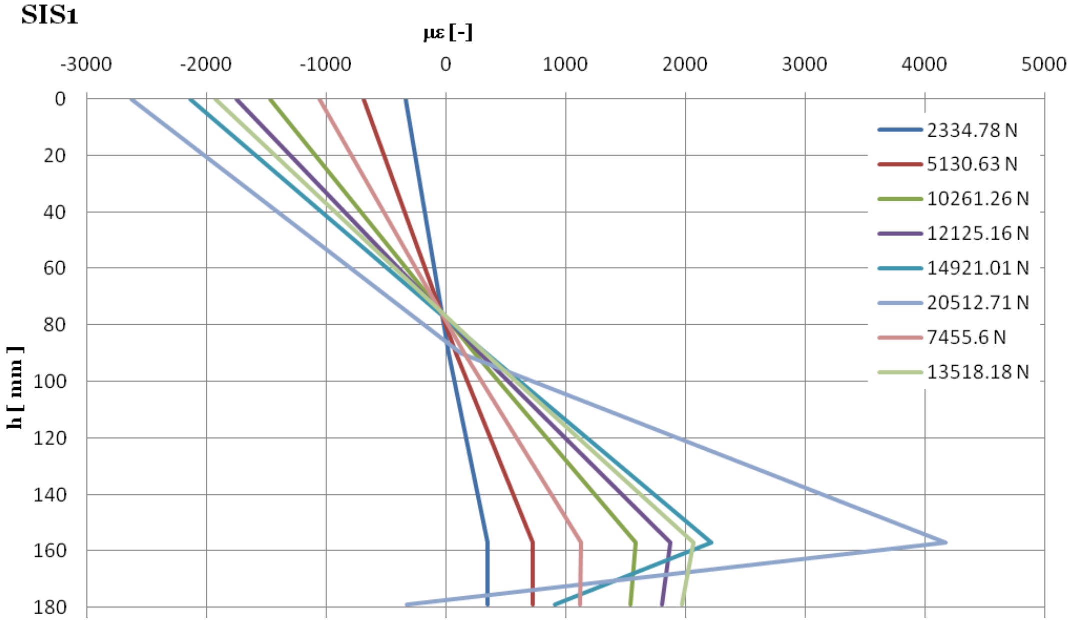

Figure 6.20 Strain distribution_SIS1

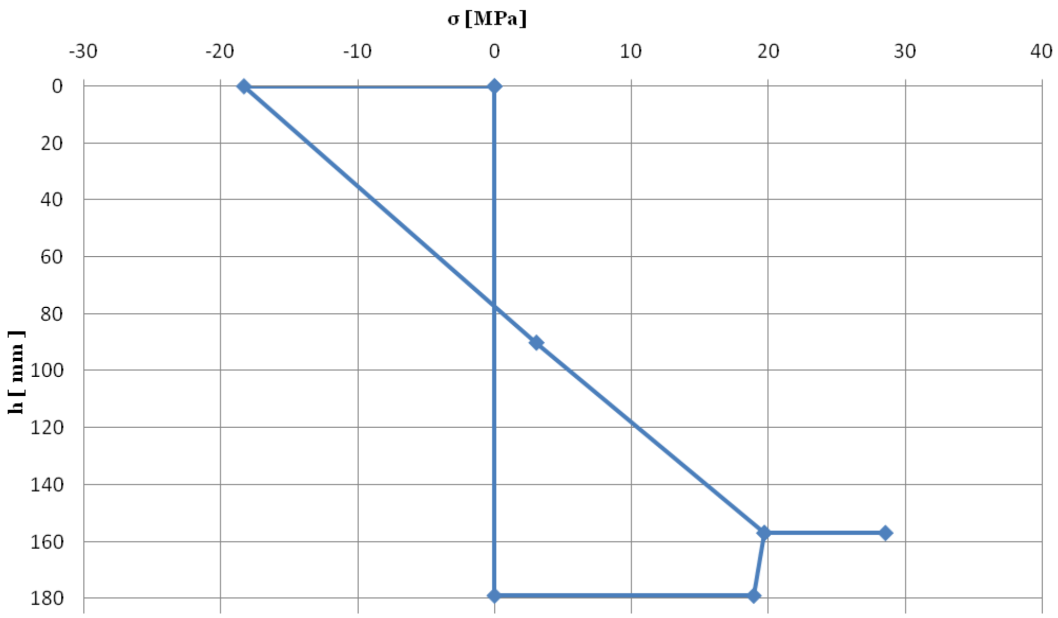

Figure 6.21 Stress distribution_ F=12125,16 N_SIS1

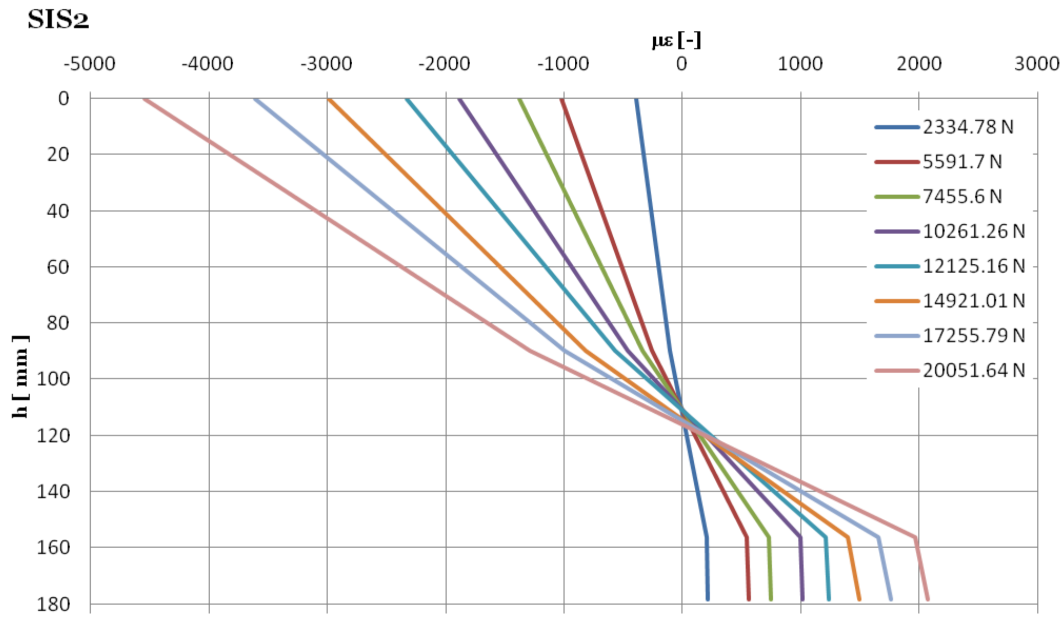

Figure 6.22 Strain distribution_SIS2

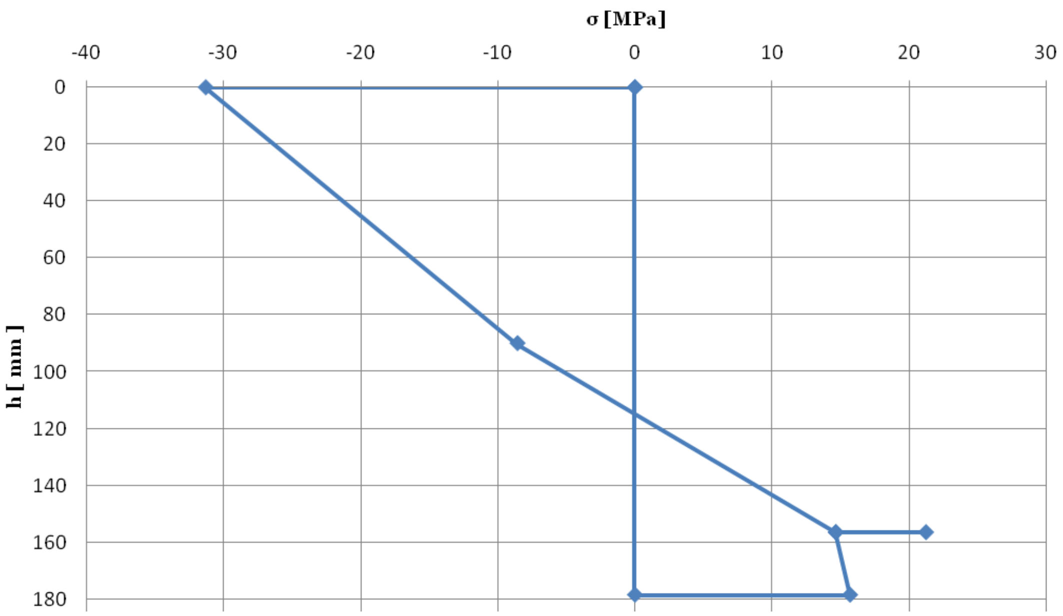

Figure 6.23 Stress distribution_ F=14921,01 N_SIS2

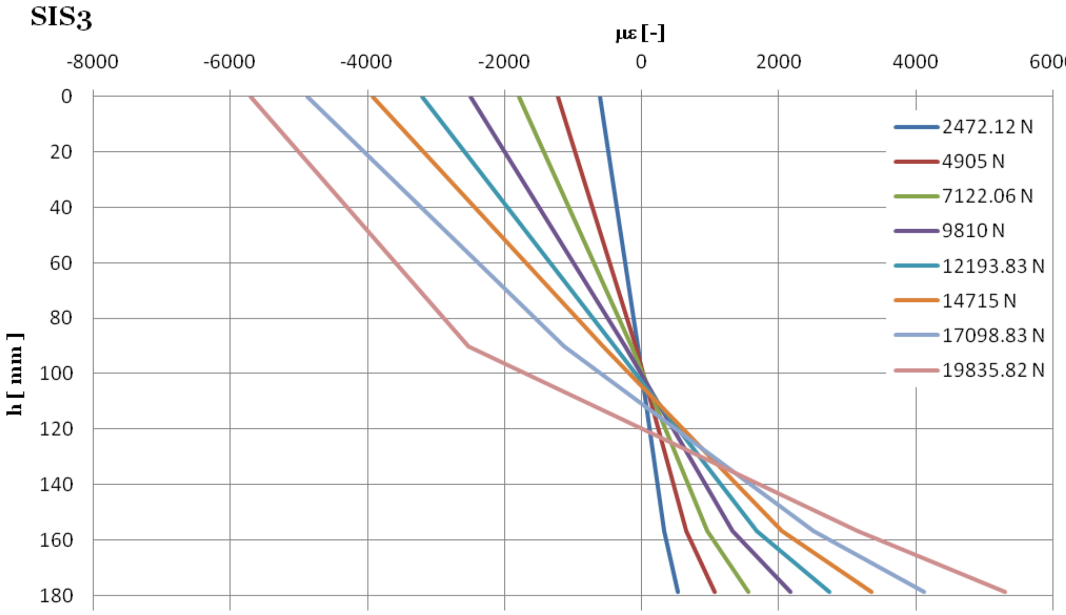

Figure 6.24 Strain distribution_SIS3

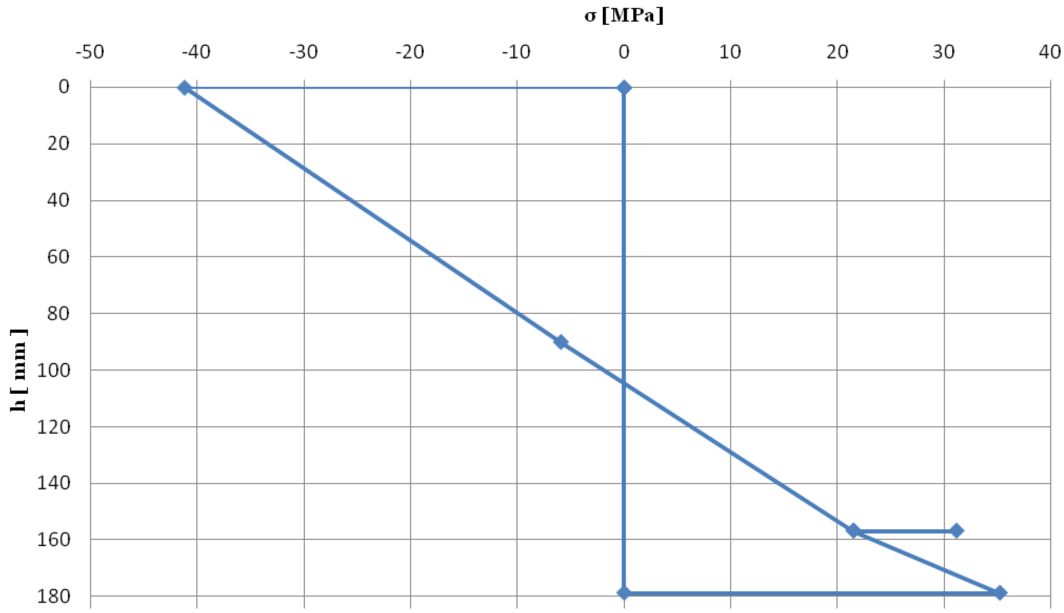

Figure 6.25 Stress distribution_ F=14715 N_SIS3

Beams with reinforcement of Vectran

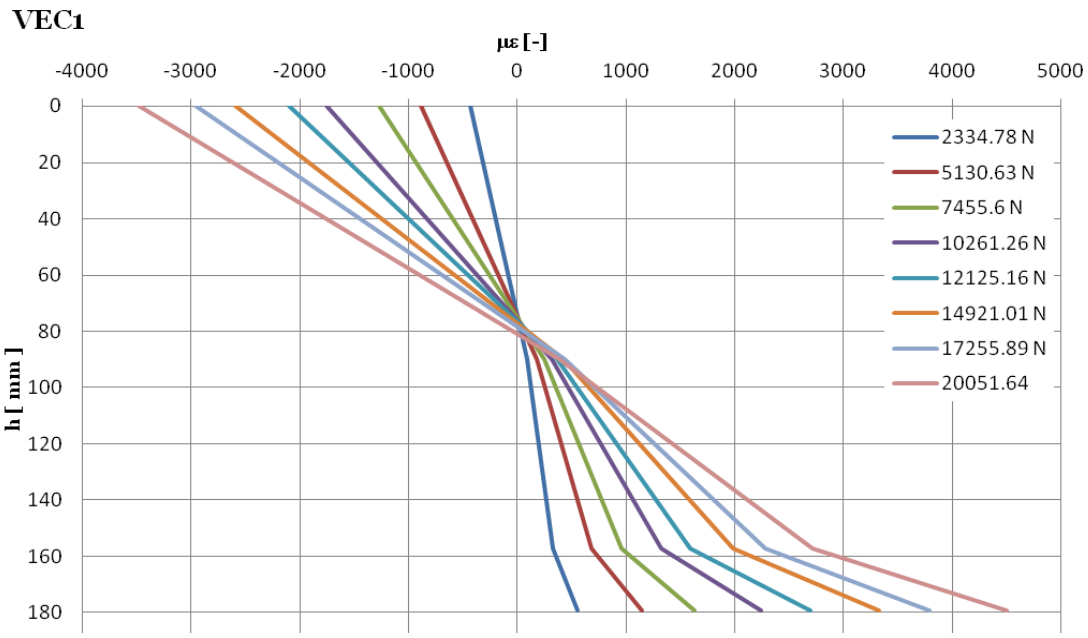

Figure 6.26 Strain distribution_VEC1

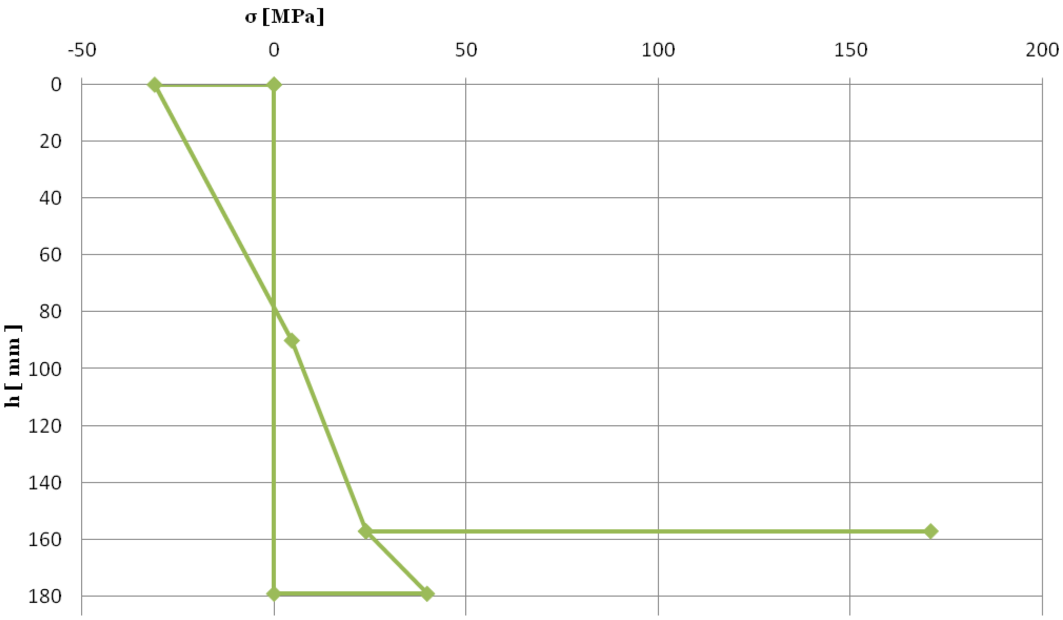

Figure 6.27 Stress distribution_ F=17255,79 N_VEC1

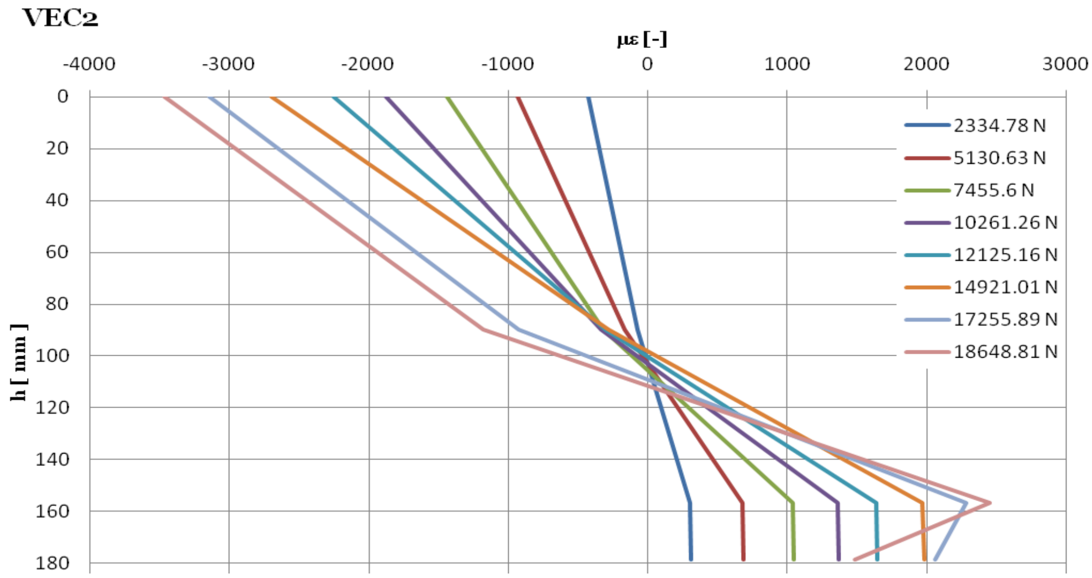

Figure 6.28 Strain distribution_VEC2

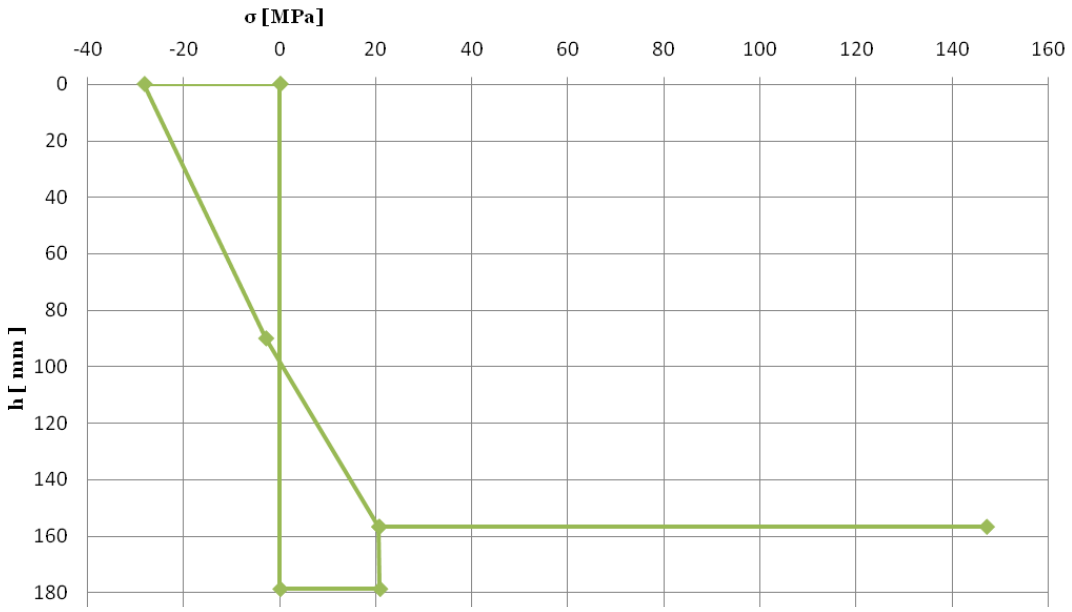

Figure 6.29 Stress distribution_ F=14921,01 N_VEC2

VEC3

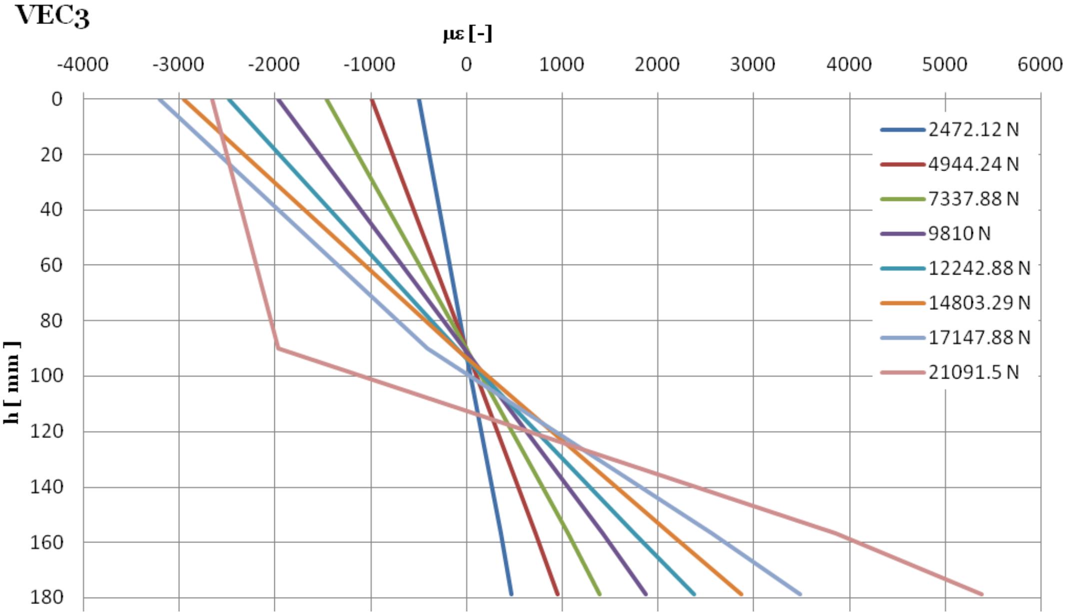

Figure 6.30 Strain distribution_VEC3

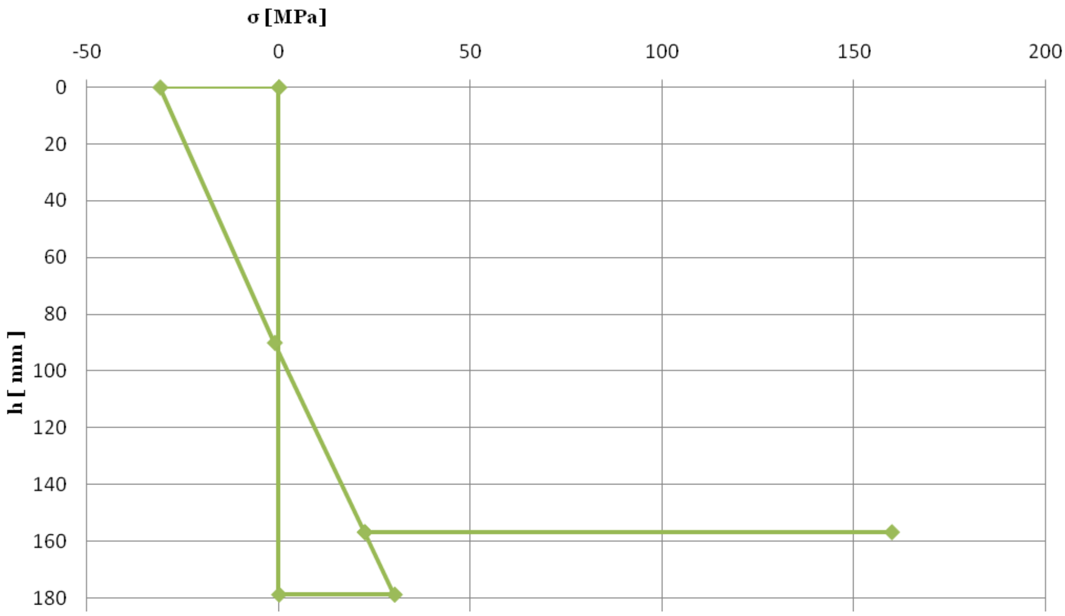

Figure 6.31 Stress distribution_ F=14803,29 N_VEC3

6.5 Conclusions

The successful use of FRP reinforcement is perhaps the most significant development in laminated beam technology during the last 40 years. One of the most important steps in this progress is that of matching the strain of fiber composites to timber. The possibility of using fiber as reinforcement for glulam timber elements is of interest, due to the improved durability of the system, low cost manufacturing and to the easier and faster application guaranteed.

Experimental program was conducted in order to investigate the effectiveness of fibers as flexural reinforcement of glulam beams. Three different type of fibers were used at the tension side of the glulam section: Curaua', Sisal and Vectran. The bending behaviour of the beams was studied through their moment- curvature curves, load-deflection characteristics and failure mode. Strain distribution across the depth of the beam upon loading was studied as well.

The unreinforced glulam beams demonstrated linear elastic behaviour and exhibited brittle tensile-flexural failures when compared to pseudo-ductile behaviour of the reinforced beams. The reinforcing influences the plastic behaviour of the beam, which otherwise is not so predominant due to the low tensile strength of the timber. The rupture of the reinforced glulam beams was always reached due to the crisis of the timber.

Strategically positioned, the reinforcement in the more highly stressed tension region at the bottom of the beam allows for timber compression fibres to reach their yield strains and, hence, better utilization of the compressive properties of the timber.

The experiments show that the introduction of fiber as reinforcement in the cross section reduces the variability in results. The reinforced specimens were more consistent in their properties and behaviour. This indicates the ability of the fibers to reduce the effect of natural defects in timber. Moreover, the fiber that has shown better performance is the fiber of Sisal that could be due to the character of the fiber that , as a natural fiber, is more compatible with a natural material such as wood.

Further research is necessary to examine the influence of using different adhesive and different geometries on the strength and stiffness of glulam beams for both the serviceability and ultimate limit states.

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