KAUNAS UNIVERSITY OF TECHNOLOGY

MECHANICAL ENGINEERING AND DESIGN FACULTY

Raghul Krishni Narasimhan

IMPROVING THE MECHANICAL PROPERTIES OF HONEYCOMB SANDWICH STRUCTURES

Final project for master degree

Supervisor:

Assoc. Prof. Dr**.** Daiva Zeleniakienė

KAUNAS, 2016

KAUNAS UNIVERSITY OF TECHNOLOGY

MECHANICAL ENGINEERING AND DESIGN FACULTY

PRODUCTION ENGINERRING DEPARTMENT

I APPROVE:

Head of Department: ____________________________
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Assoc. Prof. Dr. Kazimieras Juzėnas

IMPROVING THE MECHANICAL PROPERTIES OF HONEYCOMB SANDWICH STRUCTURES

Final project for Master degree

INDUSTRIAL ENGINEERING AND MANAGMENT DEPARTMENT
(code: MEM –(3/9))

Project made by:

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KAUNAS, 2016

KAUNAS UNIVERSITY OF TECHNOLOGY

MECHANICAL ENGINEERING AND DESIGN FACULTY

PRODUCTION ENGINEERING DEPARTMENT

Raghul Krishni Narasimhan

Industrial engineering and management, ME M-(3/9)

IMPROVING THE MECHANICAL PROPERTIES OF HONEYCOMB SANDWICH STRUCTURES

DECLARATION OF ACADEMIC HONESTY

_______ ___________________ 2016
Kaunas

I confirm that a final project by me, **Raghul Krishni Narasimhan**, on the subject "Improving the mechanical properties of honeycomb sandwich structures" is written completely by myself; all provided data and research results are correct and obtained honestly. None of the parts of this thesis have been plagiarized from any printed or Internet sources, all direct and indirect quotations from other resources are indicated in literature references. No monetary amounts not provided for by law have been paid to anyone for this thesis.

I understand that in case of a resurfaced fact of dishonesty penalties will be applied to me according to the procedure effective at Kaunas University of Technology.

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KAUNAS UN IVERSITY OF TECHNOLOGY

FACULTY OF MECHANICAL ENGINEERING AND DESIGN

Approved:
Head of
Production engineering
Department

(Signature, date)

Assoc. Prof. Dr. Kazimieras Juzėnas
(Name, Surname)

MASTER STUDIES FINAL PROJECT TASK ASSIGNMENT

Study programme: Industrial engineering and management

The final project of Master studies to gain the master qualification degree, is research or applied type project, for completion and defence of which 30 credits are assigned. The final project of the student must demonstrate the deepened and enlarged knowledge acquired in the main studies, also gained skills to formulate and solve an actual problem having limited and (or) contradictory information, independently conduct scientific or applied analysis and properly interpret data. By completing and defending the final project Master studies student must demonstrate the creativity, ability to apply fundamental knowledge, understanding of social and commercial environment, Legal Acts and financial possibilities, show the information search skills, ability to carry out the qualified analysis, use numerical methods, applied software, common information technologies and correct language, ability to formulate proper conclusions.

1. Title of the Project

Improving the mechanical properties of honeycomb sandwich structures

Approved by the Dean 2015 y. December m.11 d. Order No. ST17-F-11-15

2. Aim of the project

The aim of the thesis is to analyse the mechanical properties of the sandwich panels and find the optimal geometrical thickness of the sandwich with high strength and stiffness properties.

3. Structure of the project

Literature review: Sandwich structure with fiber reinforced plastic composite facesheets review: Fiber reinforce polymer composite, Sandwich structures, Manufacturing of honeycomb core sandwich structures, Testing method's

Research methodology: 1. Experimental and theoretical analysis of laminar properties of frp facesheet: Materials and geometrical description of the laminate construction, Experimental setup, and Theoretical calculation laminate properties. 2. Material modelling and analysis: Materials and finite element modelling of facesheet model, Verification of numerical model by tensile test simulation, Material and Finite element modelling of honeycomb core sandwich

Result and discussion: 1.Experimental and Theoretical properties of FRP laminate facesheet, 2. Influence of FRP Thickness on stiffness of sandwich structure, 3. Influence of FRP Thickness on coefficient of maximum deflection and equivalent stress.

Economical evaluation

4. Requirements and conditions

The honeycomb core sandwich composite comprised facesheets from wound glass fibre and polyvinylester resin and a core from recycled paper hexagonal honeycomb impregnated with polyvinylester resin. Sandwich panels were tested in laboratory using equipment's (Tensile testing machine, Force transducers, Displacement transducer, Extensometer, computer). The finite element models were generated and simulated in ANSYS 14.5.

5. This task assignment is an integral part of the final project

6. Project submission deadline: 18. 12. 2015

Given to the student of industrial engineering and management

Task Assignment received: Raghul Krishni Narasimhan
(Name, Surname of the Student) (Signature, date)

Supervisor Assoc. Prof. Dr. Daiva Zeleniakienė
(Position, Name, Surname) (Signature, date)

Contents

Krishni Narasimhan Raghul. Title of project is “Improving the mechanical properties of honeycomb sandwich structure”. Qualification degree’s final project is Master of Science in Industrial engineering and management. Supervisor: Assoc. Prof. Dr. Daiva Zeleniakienė; Kaunas University of Technology, Mechanical Engineering and Design faculty, mechanical engineering department. Kaunas, 2016.

SUMMARY

In recent day’s manufacturing industries all over the world seems to be focused on the advanced materials which are replacing the traditional materials with higher advantages in lightweight, good material properties, cost effective and suitable for manufacturing the complex geometrical structure. Fiber reinforced polymer (FRP) sandwich composites are one of the booming advanced material in industrial and commercial fields such as ships, aircraft, and general vehicles. Honeycomb core sandwich structures are especially becoming more prevalent in the field of civil engineering where the need of high structural strength and low weight is necessary. So there is a constant increase in demand for lightweight, high strength and stiffness properties and cost economical materials. These factors motivate to analyse the mechanical properties of honeycomb sandwich structures.

The aim of the master thesis is finding the optimal thickness of the facesheet material at which the high strength and stiffness properties can be obtained. The goal was implemented initially by experimental testing of the facesheet material and sandwich, theoretical analysis of the honeycomb sandwich structure, creating an appropriate numerical material model, verifying these models by comparing with experimentally obtained data, creating two different finite element (FE) models namely sandwich structure with honeycomb and neat FRP without honeycomb, investigating the two models by three point bending simulation by changing the thickness of the facesheets, the investigation was performed in three possible methods of thickness change to observe the change in strength and stiffness properties in honeycomb sandwich.

In the experimental test, material properties of the FRP facesheets and the honeycomb were obtained which was compared with calculated theoretical models and proved with closer values. Using the experimentally obtained data, numerical FE models of the facesheet and honeycomb sandwich were designed. Facesheet was verified by tension test simulation and the three point bending simulation allowed to verify sandwich structure. These material models were compared with the experimental curve and obtained a good agreement. Depending on the verified material models, a methodology to determine the optimal thickness at which high strength and stiffness properties were framed. The methodology was used for the investigation of sandwich material using two FE models first one was a sandwich structure with honeycomb and another one was without honeycomb. The models were investigated by changing the thickness of facesheets and the distance between the supports.

Keywords

Fiber reinforced polymer (FRP), honeycomb sandwich structure, finite element model (FE model), polyvinylester resin, recycled paper hexagonal honeycomb.

Krishni Narasimhan Raghul Pramonės inžinerijos ir vadybos magistro kvalifikacinio laipsnio baigiamasis darbas „Sluoksniuotų korėtų kompozitų mechaninių savybių gerinimas“. Vadovė Kauno technologijos universiteto, Mechanikos inžinerijos ir dizaino fakulteto, Mechanikos inžinerijos katedros docentė dr. Daiva Zeleniakienė. Kaunas, 2016.

SANTRAUKA

Pastaruoju metu pramonėje vyrauja tendencijos orientuotis į pažangias medžiagas, kurios galėtų pakeisti tradicines, ne tik nepabloginančios jų savybių, bet ir užtikrinančios mažesnę kainą, geresnes mechanines savybes, lengvumą, gamybos technologijų paprastumą. Sluoksniuoti korėti pluoštu armuoti plastiko kompozitai – vienos labiausiai pažangios kompozitinės medžiagos, leidžiančios pakeisti tradicines medžiagas gamyboje ir yra labai dažnai naudojamos laivų, orlaivių, transporto pramonėse. Korėtos šerdies kompozitai vis dažniau naudojami ir statybos pramonėje, kur taip pat reikalinga naudoti didelio stiprumo ir standumo medžiagas. Taigi, yra didžiulis poreikis gaminti mažo tankio ar masės konstrukcinius elementus, kurie pasižymėtų ne tik geromis mechaninėmis savybėmis, bet ir užtikrintų ekonominį efektyvumą. Todėl šis darbas yra labai aktualus ir šiuolaikiškas.

Magistro darbo tikslas – rasti optimalius korėtos sluoksniuotos medžiagos laminuojančių sluoksnių storius, su kuriais būtų užtikrintas reikiamas stiprumas ir standumas. Tikslas buvo siekiamas atliekant medžiagos laminuojančių sluoksnių atskirai ir visos korėtos struktūros kartu mechaninių savybių eksperimentinius tyrimus, naudojant nustatytas mechanines savybes sukuriant analitinius bei baigtinių elementų skaitinius modelius, pastaruosius verifikuojant sulyginus skaičiavimų rezultatus su eksperimentinių tyrimų metu gautais rezultatais, kuriant skirtingus modelius vien tik iš laminuojančios medžiagos sluoksnių ir įterpiant korėtą šerdį tarp jų, tiriant medžiagas tritaškio lenkimo bandymu ir varijuojant laminuojančių sluoksnių storius bei atstumą tarp atramų tritaškio lenkimo tyrime.

Eksperimentinių tyrimų metu atskirai buvo nustatomos pluoštu armuotų plastikų ir sluoksniuotos struktūros iš šių kompozitų laminuojančių sluoksnių su korėta šerdimi mechaninės savybės. Su eksperimentiniai duomenimis buvo palyginti skaičiuotinais metodais gauti rezultatai. Laminuojančių sluoksnių vienašio tempimo bandymo rezultatai gerai sutapo su baigtinių elementų metodu sukurto modelio duodamais skaičiavimo rezultatais, o korėtos struktūros modelis buvo verifikuojamas lyginant modeliavimo duomenis su tritaškio lenkimo eksperimentu gautais rezultatais. Šis palyginimas parodė gerą duomenų sutapimą, todėl buvo nuspręsta modelius laikyti verifikuotais. Šių verifikuotų modelių pagrindu buvo modeliuojami kintami parametrai: laminuojančių sluoksnių storis, atstumas tarp tritaškio tyrimo atramų.

Reikšminiai žodžiai

Pluoštu armuotas plastikas, korėta sluoksniuota struktūra, baigtinių elementų modelis, poli vinilo esterio derva, perdirbto popieriaus šešiakampis korys

INTRODUCTION

In recent day's manufacturing industries all over the world seems to be focused on the advanced materials which are replacing the traditional materials with higher advantages in lightweight, good material properties, cost effective and suitable for manufacturing the complex geometrical structure. Fiber reinforced polymer (FRP) sandwich composites are one the booming advanced material in industrial and commercial fields such as ships, aircraft, and general vehicles. Honeycomb core sandwich structures are especially becoming more prevalent in the field of civil engineering where the need of high structural strength and low weight is necessary. So there is a constant increase in demand for lightweight, high strength and stiffness properties and cost economical materials. These factors are directly or indirectly related to the mechanical properties of honeycomb sandwich structures.

Usually, the optimal geometrical structure at with higher mechanical properties are the main motive in this material research. Often there is a correlation to design and manufacture sandwich panels with much precise geometry and optimal properties. Normally the existing sandwich panels are designed and manufactured with the higher factor of safety in the thickness and mechanical properties required for the particular application. This may be a reasonable solution. But when we consider for complex geometry and larger design, it's not so comparatively easy, dimensional restrictions, and material consumption and production cost will be the major issues.

In the case of finding the optimal thickness of the sandwich structural at which the strength and stiffness properties higher can be the one odd the possible solutions. A honeycomb sandwich panel comprises of facesheet with wounded glass fibre and polyvinylester resin and the core made of recycled paper hexagonal honeycomb impregnated in polyvinylester resin was experimentally tested depending on the obtained material properties a numerical finite element material models were created in ANSYA14.5. And verified. Based on the verified model a methodology used to investigate and find the possible optimal thickness with good strength and stiffness properties of the sandwich panel were obtained.

The aim of thesis

The aim of the thesis is to analyse the mechanical properties of the sandwich panels and find the optimal geometrical thickness of the sandwich with high strength and stiffness properties.

The task of thesis

1. To perform the experimental testing of sandwich panels.
2. To perform the theoretical analysis of the sandwich panels.
3. To generate numerical FE models of facesheet and sandwich panels.
4. To verify the material models with experimental data.
5. To generate models of sandwich with honeycomb and without honeycomb.
6. To propose a possible method for investigating the models.
7. To perform the economic evaluation of sandwich panel.

1. SANDWICH STRUCTURE WITH FIBER REINFORCED PLASTIC COMPOSITE FACESHEETS

1.1. INTRODUCTION TO COMPOSITE MATERIALS

The composite material is a material consisting of two or more physically and (or) chemically distinct phase, suitably arranged or distributed. A composite material usually has characteristics that are not depicted by any of its components in isolation [1]. Using this definition, it can be determined that a wide range of engineering materials falls into this category. For example, Fiberglass sheet is a composite since it is made of glass fibres impregnated in a polymer [2]. Composites, the wonder materials are becoming an essential part of present materials due to the advantages such as low weight, high fatigue strength, corrosion resistance, and faster assembly [3].

The incorporation of several different types of fibres into a single matrix has led to the development of composites. The behaviour of composites is a weighted sum of the individual components in which there is a more favourable balance between the advantages and disadvantages [4]. Also, using a hybrid composite that contains two or more types of fibre, the advantages of one type of fibre could complement with, what are lacking in the other. As a consequence, a balance in cost and performance can be achieved through proper material design [5].

The advanced composite materials are mostly used in aerospace industries. These composites have high-performance reinforcement of thin diameter in the matrix material such as polymer composites. These materials have found applications in commercial industries. In various cases, using composite is more efficient. For example, in the highly competitive airline market, everyone is looking for ways to lower the overall mass of the aircraft without decreasing the stiffness and strength of its components. This is possible by replacing conventional metal alloys with composite materials. Even if the composite material costs may be higher, the reduction in the number of parts in an assembly and the savings in fuel costs make them more profitable.

Composites offer several other advantages over conventional materials. These may include improved strength, stiffness, fatigue and impact resistance, thermal conductivity, corrosion resistance [6].

1.2. FIBER REINFORCE POLYMER COMPOSITE

Fiber reinforced polymer (FRP) composites were first developed during the 1940s, for military and aerospace applications. Considerable advances have been made since then in the use of this material and applications developed in the construction sector. FRPs have been successfully used in many construction applications including load bearing and infill panels, pressure pipes, tank liners, roofs, and complete structures where FRP units are connected together to form the complete system in which the shape provides the rigidity.

FRP is an acronym commonly used in the composite industry and it refers to plastic and polymer materials that are reinforced with structural fibre such as fiberglass, carbon fibre, or aramid fibre. The polymer is usually an epoxy, vinyl ester or polyester thermosetting plastic, and phenol formaldehyde resins are still in use. FRPs are commonly used in the aerospace, automotive, marine, and construction industries

The FRP composite is produced in the form of laminate composite materials which consist of stacks of layers, each layer usually composed by a matrix of polymeric material and fibers oriented in a specific direction as shown in Fig 1.

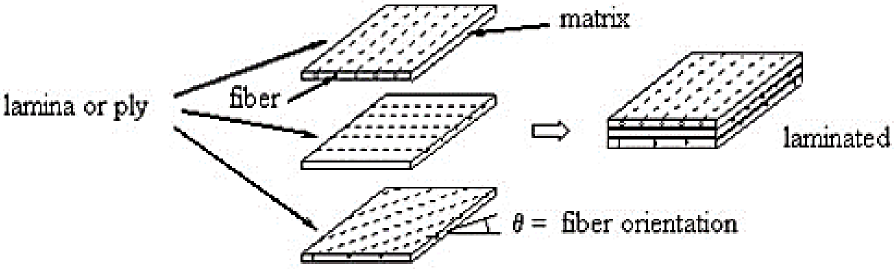

Fig 1.1. The structure of the laminate [8]

Fiber-reinforced composite materials consist of the fiber of high strength and modulus embedded into a matrix with distinct interfaces between them. So they produce properties of which cannot be achieved when they act alone. So, mechanical properties of FRP composite laminates depend on the material of each layer, the number of layers, the thickness of each layer and the fiber orientations in each layer. The ply thicknesses are often predetermined and the ply orientations are usually restricted to a small set of angles due to manufacturing constraints. This leads to problems of discrete or stacking sequence optimization. [7]

When the resin systems are combined with reinforcing fibres such as glass, carbon and aramid, that exceptional properties can be obtained. The resin matrix spreads the load applied to the composite between each of the individual fibres and also protects the fibres from damage caused by abrasion and impact. High strengths and stiffness, ease of moulding complex shapes, high environmental resistance all coupled with low densities, make the resultant composite superior to metals for many applications. [9]

The overall properties of the composites determined by the properties of the fibre, properties of the resin, the ratio of fibre to the resin in the composite (Fibre Volume Fraction), the geometry and orientation of the fibres in the composite as shown in Fig 2.

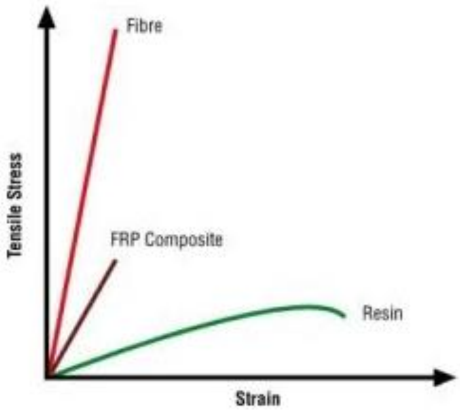

Fig 1.2. Overall properties dependence of composite [9]

The common fibers for commercial use are glass fibers, carbon fiber and also Kevlar fiber. Most commonly these fibers are used in the form of laminates, which are made by stacking a number of thin layers of fibers and matrix and consolidating them into the desired thickness [10].

1.3. SANDWICH STRUCTURES

Sandwich structured composites are a particular class of composite materials which have become very popular due to high specific strength and bending stiffness. The low density of these materials makes them especially suitable for use in aeronautical, space and marine applications. Sandwich panels are composite structural elements, consisting of two thin and stiff facesheets and separated by a thick layer of light weight and a stiff material called core. [11]

The faces and the core material are bonded together with an adhesive to facilitate the load transfer mechanisms between the components. This particular layered composition creates a structural element with both high bending stiffness, bending strength-weight ratios. [12]

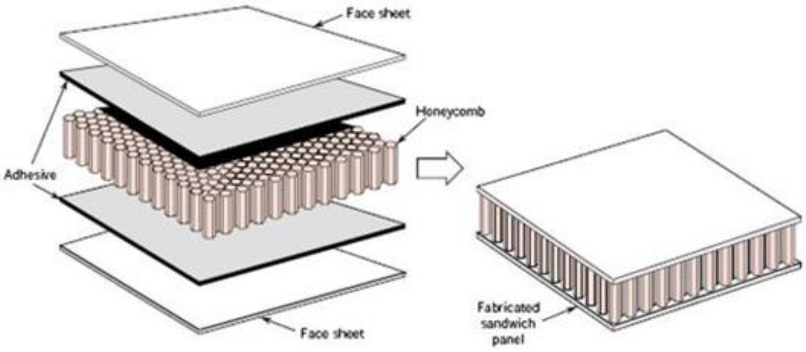

Fig 1.3. Construction of honeycomb core sandwich panel [13]

The construction of honeycomb core sandwich structures is shown in Fig 1.3. The first layer is the facesheet. This layer is the primary layer of the sandwich structure called as skin and the skin is bonded with the honeycomb core by the adhesive layer. The adhesive may be thermoset plastic or thermoplastic.

By splitting a solid laminate down the middle and separating the two halves with a core material the result is a sandwich panel. The new panel weighs little more than the laminate, but its flexural stiffness and strength are much greater by doubling the thickness of the core material the difference is, even more, striking [13].

1.3.1.Composite face sheet

Composite face-sheets and honeycombs are bonded as two distinct solid phases through a secondary bond. In general, a fully cured honeycomb is bonded to the composite facesheets as shown in Fig 1.4. by either of the following two methods.

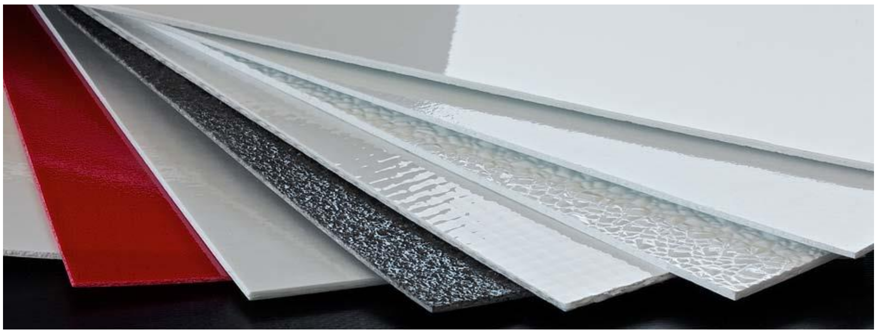

Fig 1.4. Fiber reinforced polymer facesheet used in the sandwich structure [15]

An adhesive film is placed on the top and the bottom surfaces of the honeycomb upon which cured/uncured prepregs are placed. This whole assembly is placed in an autoclave to cure the adhesive (resin). During the curing process, the resin from the film plasticizes/melts. The resin flows and creates a bond between the prepregs and the honeycomb walls [14].

The facesheet thickness ranges from 0.25mm to 40 mm according to the design specification. The main reason to use composite material is that they have higher resistance to most of the environments and they can be used by most individuals without a major investment in equipment also they can be easily shaped into complex shapes. The use of the composite material must be clear in order to select proper constituent matrix material and reinforcement as shown in Fig 1.5.

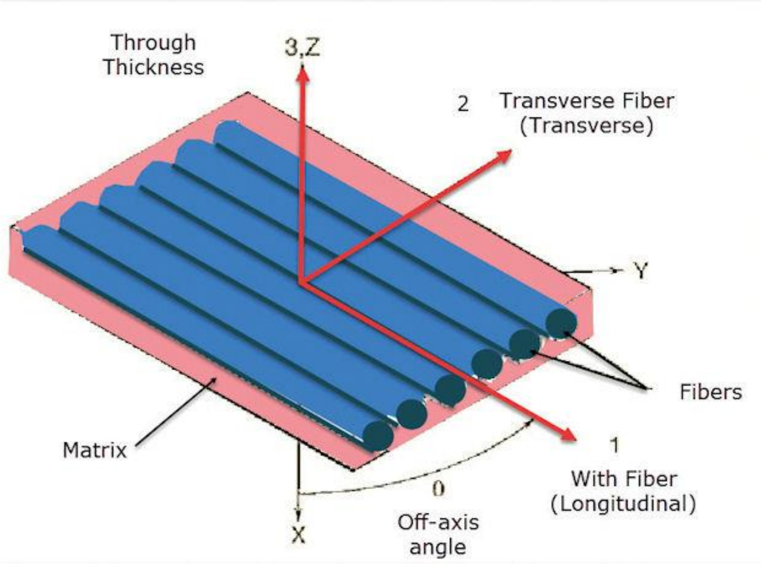

Fig 1.5. Fiber orientation in polymer matrix

In composite facesheets, the fiber carries the load applied on the composite structure, gives high strength and stiffness, high thermal resistance and other structural properties. Matrix materials work as a binder to keep the fibers together and transfer the load to the fibers and also protect the fibers from the external damages and natural and chemical attacks [16].

Facesheet Matrix Materials

Selecting a proper matrix material is an important step in preparing the facesheet materials in which the properties of the matrix material and the manufacturing conditions must be considered.

The resin types are:

1. Thermosetting resin.
2. Thermoplastic resin

Epoxy, vinyl ester and polyester are the most common resin used are the thermosetting resin. These resins are renowned for their superior mechanical properties when used as matrix material. This resin is added with fiber and formed into a solid laminate or prepregs according to the application during the manufacturing process called curing. This process involved heating and one is more temperatures. In the case of thermoplastic, it has the properties of plastic deformation easily when compared to thermoset plastics. So they have different properties when compared to each other. Epoxy was used in weight-critical, high strength, and dimension accurate, but polyester resins are less expensive, more corrosion resistance, they are more widely used [17].

1.3.2.Core materials

The main part of the sandwich structure is core material, in most of the sandwich structure in plain loads and bending loads are carried by the facesheets and the core carries the transverse shear load. The core materials are generally divided into four types solid, honeycomb, web core and truss core.

The inner skin is laminated onto the top of the core material effectively sealing it. Sandwich core laminates of this type are used to stiffen various composite applications such as boat hulls, automobile hoods, moulds, and aircraft panels. By increasing the core thickness, you can increase the stiffness of the sandwich without substantially increasing weight and cost.

The most common types of core materials are:

- Honeycomb
- Vinyl Sheet Foam
- End Grain Balsa
- Polyurethane Foam
- Mix and Pour Polyurethane Foam

Honeycomb

Honeycomb is a series of cells, nested together to form panels similar in appearance to the cross-sectional slice of a beehive as shown in Fig 1.6. In its expanded form, honeycomb is 90-99 % open space. Honeycomb is fire retardant, flexible, lightweight, and has good impact resistance. It offers the best strength to weight ratio of the core materials. Honeycomb is used primarily for structural applications in the aerospace industry. Parts which require minimum weight often employ Honeycomb sandwich cores. [17]

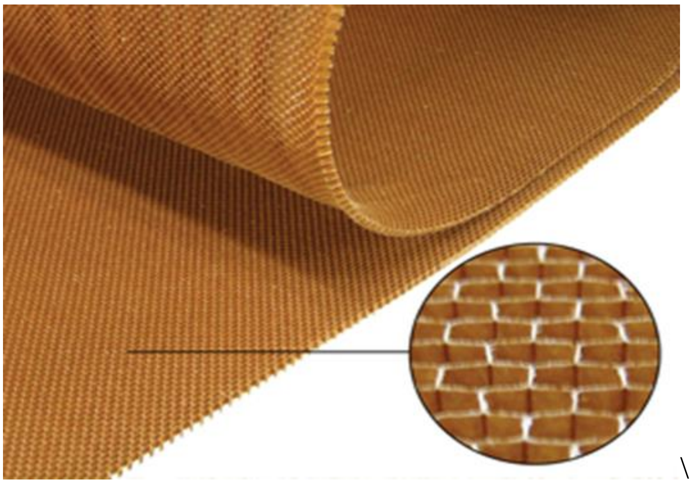

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Fig 1.6. Honeycomb core [18]

Vinyl Sheet Foam

Vinyl sheet foam is shown in Fig 1.7. is one of the most versatile core materials on the market. It is a rigid, closed cell material that resists hydrocarbons, alkalis, dilute acids, methyl alcohol, sea water, gasoline, diesel oil, and it is self-extinguishing. It has been used extensively in aircraft and performance automotive structures, but it can be applied anywhere that high properties and easy handling are needed. Vinyl foam can be thermoformed in an oven or with a heat gun while applying gentle pressure. For ultimate peel strength, use a perforation roller to increase the surface area of the foam. The peel strength will increase an additional 15-20% after perforation [19].

Fig 1.7. Vinyl Sheet Foam [19]

End Grain Balsa

End-grain balsa is the most widely used core material. It is both a relatively high strength core and less expensive than vinyl or honeycomb. It achieves its high compression strength because on a microscopic level it has a honeycomb type of structure yet is quite dense. It is easy to cut and bevel and is available in 29x49 inch sheets. The individual small blocks of end grain balsa are bonded to a light scrim fabric which makes the sheet quite flexible as shown in Fig 1.8.

Fig 1.8. End Grain Balsas [20]

Polyurethane Foam

This sheet foam shown in Fig 1.9 is a rigid, closed cell material with excellent thermal insulation and flotation properties. This core has been at the heart of the marine industry for decades and is fairly inexpensive when a lower property cored laminate is needed. It is compatible with both polyester and epoxy resin systems.

Fig 1.9. Polyurethane Foam [21]

Mix and Pour Polyurethane Foam

This foam is a rigid, closed cell material with excellent thermal and floatation properties. While it is not generally suited to the classic sandwich core laminate, it can be poured into any closed cavity to stiffen the structure. The free rise density is 0.9 kg per cubic meter but closed mild techniques can increase the density when required. Small amounts of this foam may be added to the honeycomb to fill the cells. The filled honeycomb is then much easier to bevel and shape. [21]

1.4. MANUFACTURING OF HONEYCOMB CORE SANDWICH STRUCTURES

1.4.1. Manufacturing of honeycomb core

The expansion process

Honeycomb is made of paper, a form of paper made of aromatic polyamide -aramid- fibres. The paper provides high electrical, mechanical and chemical integrity, moisture insensitivity, radiation and flame resistance. These unique characteristics make it the perfect solution for many applications, especially those which need to be lightweight and fire retardant.

An initial unstable expanded paper honeycomb structure is dipped into a phenolic resin to produce a honeycomb core which (after cure) becomes very strong. Subsequent dipping cycles can increase strength and weight of the resulting product. Honeycomb cells can also be filled with

Composites component rigid foam for a greater bond area for the skins. Composites honeycomb is manufactured by the expansion method which is a quite simple process. Honeycomb starts out as flat sheets of paper material as shown in Fig 1.10. Strips of adhesive are “printed” on the paper in a staggered pattern. Next, the sheets of paper are stacked together and cured to form an “HOBE” (honeycomb before expansion) block. The HOBE is pulled apart from its sides (or “expanded”), much like an accordion, forming an expanded honeycomb block, that now incorporates the hexagon cell shapes. This initially unstable expanded paper honeycomb cell structure is dipped into a phenolic resin. Once cured, the blocks are cut to the honeycomb sheets with the desired thickness. [22]

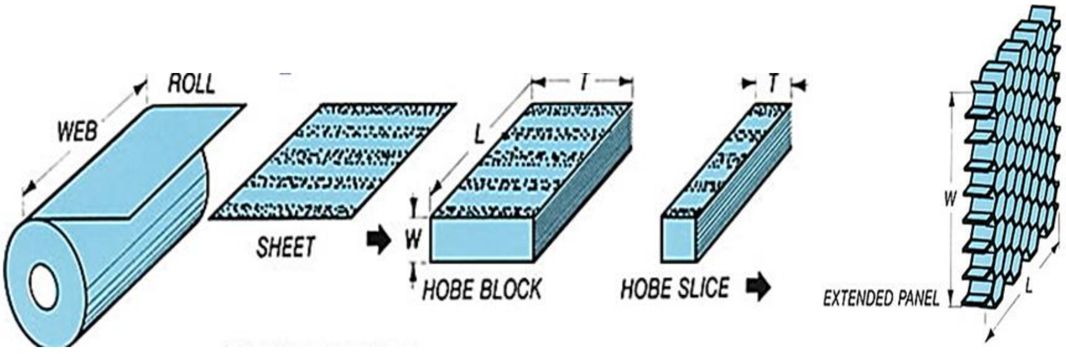


Fig 1.10. The expansion process [22]

This manufacturing technique increases the mechanical properties of the core by stabilizing the cell walls and increases thermal and acoustic insulation properties. The behaviour of the honeycomb structures is orthotropic; hence, the panels react differently depending on the orientation of the structure. Therefore, it is necessary to distinguish between the directions of symmetry, the so-called L or ribbon direction and W or transverse-to-ribbon direction. The shear modulus and strength in the L direction are roughly twice than this in the W direction.

Corrugation process

Another approach based on a corrugation process is illustrated in Fig 1.11. In this approach, a metal sheet is corrugated and then stacked into a block.

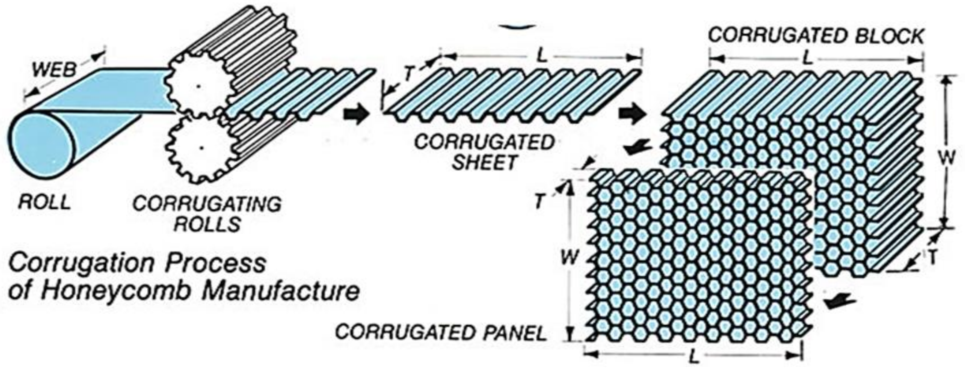


Fig 1.11. Corrugation process [22]

The sheets are bonded by welding (or any suitable method) together and the core sliced to the desired thickness and the corrugated layers either adhesively bonded or welded to face sheets. Shows the process for forming a hexagonal honeycomb core; however this process may be used for numerous additional topologies including square and triangular shaped cells.

1.4.2. Sandwich structure

Hand layup

Hand lay-up is an open moulding method suitable for making a wide variety of composites products including boats, tanks, bath ware, housings, RV/truck/auto components, architectural products, and many other products ranging from very small to very large. Production volume per mould is low; however, it is feasible to produce substantial production quantities using multiple moulds.

Moulds

Simple, single-cavity moulds of fiberglass composites construction are generally used. Moulds can range from very small to very large and are the low cost of composites moulds.

Process Description

Gel coat is first applied to the mould using a spray gun for a high-quality surface. When the gel coat has cured sufficiently, roll stock fiberglass reinforcement is manually placed on the mild as shown in Fig 1.12. The laminating resin is applied by pouring, brushing, spraying, or using a paint roller. FRP rollers, paint rollers, or squeegees are used to consolidate the laminate, thoroughly wetting the reinforcement, and removing entrapped air. Subsequent layers of fiberglass reinforcement are added to build laminate thickness. Low-density core materials, such as end-grain balsa, foam, and honeycomb, are commonly used to stiffen the laminate to produce sandwich construction.

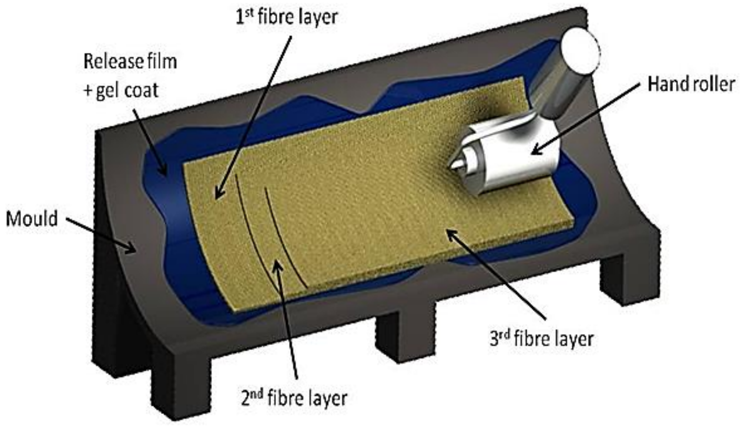


Fig 1.12. Hand layup [23]

Vacuum bagging can be used with wet-lay laminates and prepregs advanced composites. In wet lay-up bagging the reinforcement is saturated using hand lay-up, then the vacuum bag is mounted on the mild and used to compact the laminate and remove air voids.

In the case of pre-impure advanced composites moulding, the prepregs material is laid-up on the mild, the vacuum bag is mounted and the mild is heated or the mould is placed in an autoclave that applies both heat and external pressure, adding to the force of atmospheric pressure. The prepregs-vacuum bag-autoclave method is most often used to create advanced composites used in aircraft and military products.

Resin transfer moulding

Resin transfer moulding is an intermediate volume moulding process for producing composites. The RTM process is to inject resin under pressure into a mould cavity as shown in Fig 1.13. RTM can use a wide variety of tooling, ranging from low-cost composite moulds to temperature controlled metal tooling. This process can be automated and is capable of producing rapid cycle times. Vacuum assist can be used to enhance resin flow in the mould cavity.

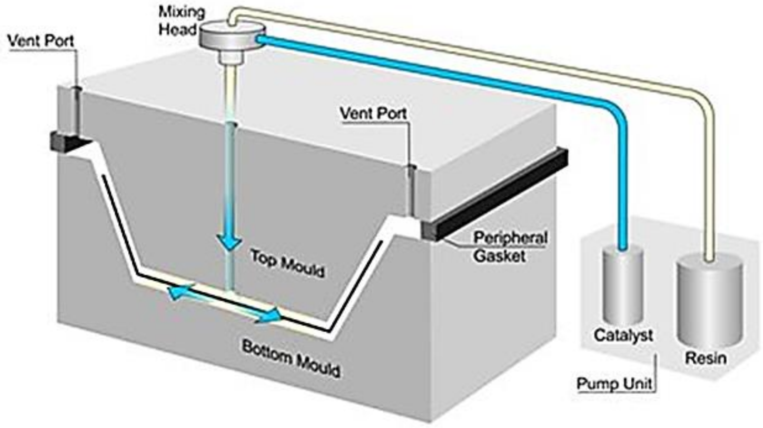


Fig 1.13. Resin transfer moulding [23]

Process Description

The mild set is gel coated conventionally if required. The reinforcement (and core material) is positioned in the mould and the mild is closed and clamped. The resin is injected under pressure, using mix/meter injection equipment, and the part are cured in the mould. The reinforcement can be either a preform or pattern cut roll stock material. Preforms are reinforcement that is pre-formed in a separate process and can be quickly positioned in the mould and the finished part is shown in Fig 1.14. RTM can be done at room temperature; however, heated moulds are required to achieve fast cycle times and product consistency. Clamping can be accomplished with perimeter clamping or press clamping.

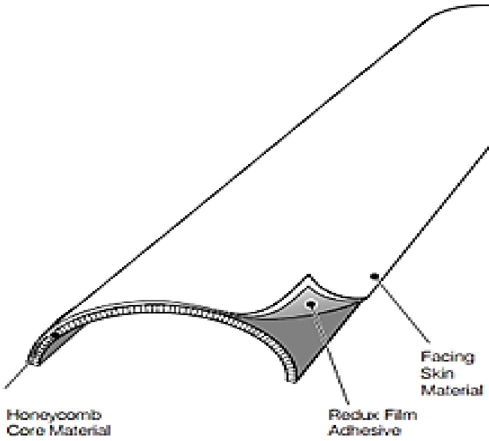


Fig 1.14. Finished part [23]

Moulds

RTM can utilize either "hard" or "soft" tooling, depending upon the expected duration of the run. Soft tooling would be either polyester or epoxy moulds, while hard tooling may consist of cast machined aluminium, electroformed nickel shell, or machined steel moulds. RTM can take advantage of the broadest range of tooling of any composites process. Tooling can range from very low cost to very high cost, long life melds.

Vacuum Bagging

The mechanical properties of open-mould laminates can be improved with vacuum bagging. By reducing the pressure inside the vacuum bag, external atmospheric pressure exerts the force on the bag as shown in Fig 1.15.

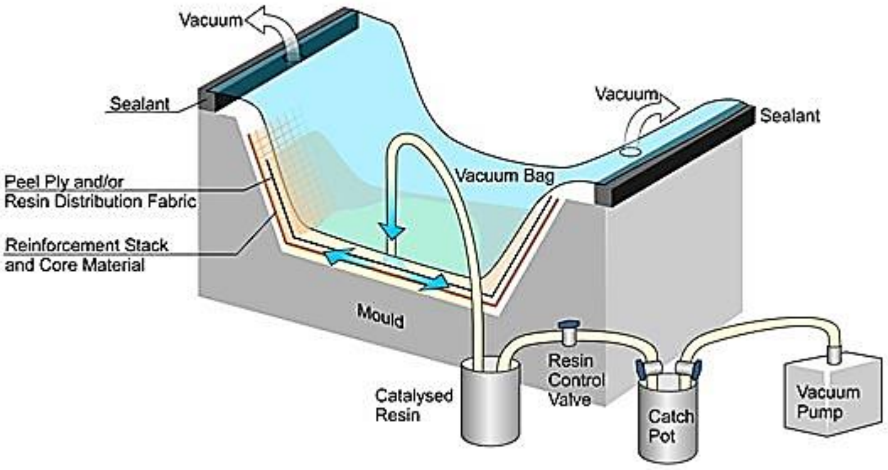


Fig 1.15. Vacuum Bagging [23]

The pressure on the laminate removes entrapped air, excess resin, and compacts the laminate. A higher percentage of fibre reinforcement is the result. Additionally, vacuum bagging reduces styrene emissions. Vacuum bagging can be used with wet-lay laminates and prepregs advanced composites. In wet lay-up bagging the reinforcement is saturated using hand lay-up, then the vacuum bag is mounted on the mild and used to compact the laminate and remove air voids.

In the case of pre-impure advanced composites moulding, the prepregs material is laid-up on the mild, the vacuum bag is mounted and the mild is heated or the mould is placed in an autoclave that applies both heat and external pressure, adding to the force of atmospheric pressure. The prepregs-vacuum bag-autoclave method is most often used to create advanced composites used in aircraft and military products.

Process Description

In the simplest form of vacuum bagging, a flexible film (PVA, nylon, Mylar, or polyethylene) is placed over the wet lay-up, the edges sealed, and a vacuum drawn. A more advanced form of vacuum bagging places a release film over the laminate, followed by a bleeder ply of fiberglass cloth, non-woven nylon, polyester cloth, or other material that absorbs excess resin from the laminate. A breather ply of a non-woven fabric is placed over the bleeder ply, and the vacuum bag is mounted over the entire assembly. Pulling a vacuum from within the bag uses atmospheric pressure to eliminate voids and force excess resin from the laminate. The addition of pressure further results in high fibre concentration and provides better adhesion between layers of sandwich construction. When laying non-contoured sheets of PVC foam or balsa into a female mould, vacuum bagging is the technique of choice to ensure proper secondary bonding of the core to the outer laminate.

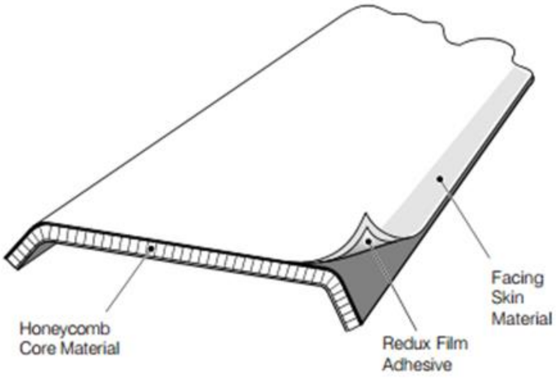


Fig 1.16: Finished part [23]

Heated Press

Generally used for the production of a flat board or simply preformed panels. Ideally, the panels should be assembled ready as shown in Fig 1.17 for curing as a single shot process. This method is suitable for metallic and prepregs (pre-impregnated) facing skins.

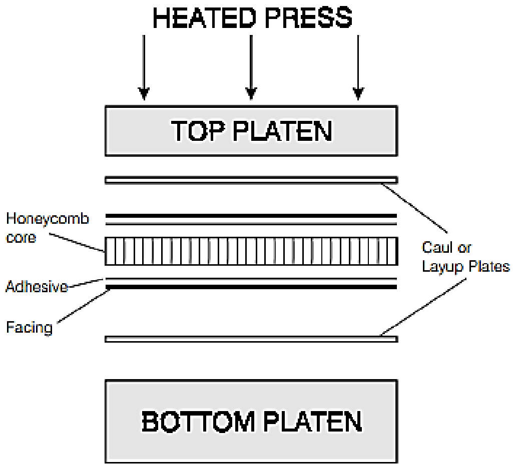


Figure 1.17. Heated Presses

Alternatively, prepregs facing skin materials may be pre-cured by using a press, and subsequent bonding with a film adhesive layer. The range of film adhesives is well suited for these production methods. Integrally bonded items such as extruded bar sections and inserts may be included and located by the honeycomb core or with simple tooling.

1.5. TESTING METHOD’S

1.5.1. Honeycomb core material testing

Three types of sandwich beam specimens are fabricated and tested in this with entangled glass fibre, honeycomb and foam as core materials. The skins for all the sandwich beams used are made of glass woven fabric. The sandwich beam specimens are fabricated using an autoclave and an aluminium mould. The skin and the core are cured simultaneously in order to have an excellent bond.

Tensile testing of honeycomb

The test specimens measured in between the locating pins. The specimen width is parallel to the node bonded areas. In a honeycomb cell, the node refers the bonded portion of adjacent ribbon sheets of paper, while the free wall is the cell wall section of the single unbounded sheet. Nine locating pins were inserted in each pair of end plates for the tests in the X2-directionas shown in Fig 1.18 (b), and six locating pins for the tests in the X1-direction as shown in Fig 1.18 (b) The test was considered void whenever failure occurred at the ends, and a new test was performed [24].

(a) (b)

Fig 1.18. (a) Tensile test of a honeycomb in the X1-direction. (b) Tensile test of a honeycomb in the X2-direction [24]

Compression testing

The compressive tests were carried out to determine the elastic modulus of the bare honeycomb core in the out-of-plane direction for specimens. Flat metal plates were used to crush entire specimens at a slow displacement rate shown in Fig 1.19. , so as to ensure an even distribution of load throughout the core. It was assumed that during crushing, the change in cross-sectional area of the cell walls was negligible, and it would not affect the elastic modulus significantly.

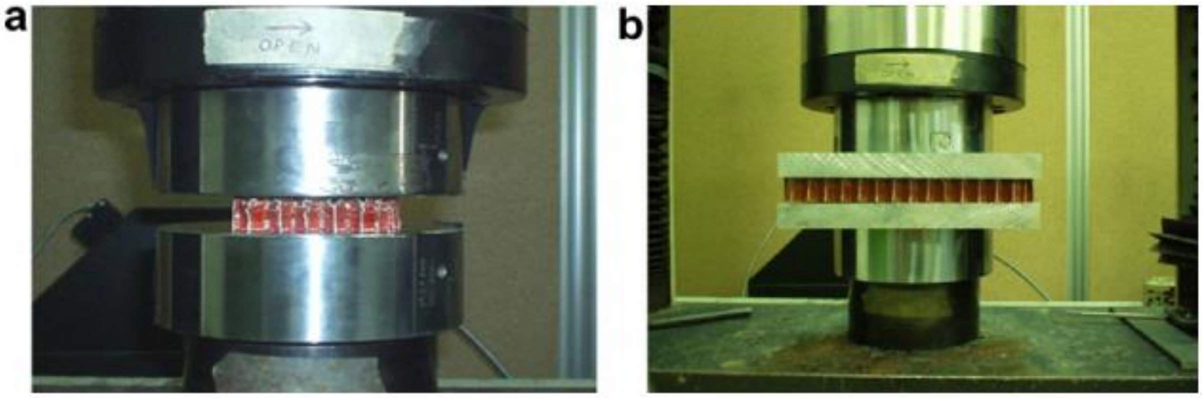


Fig 1.19. Compressive tests on bare honeycomb core. [25]

1.5.2. Compression test

Principal

A compression force is applied in an axial direction to the faces of a rectangular parallelepiped test specimen is calculated.

If the value of the maximum stress corresponds to the relative deformation of less than 10% it is noted as “compressive strength” otherwise, the compressive stress at 10% relative deformation is calculated and its value noted as the “compressive stress at 10% relative deformation” [26].

Apparatus

1. Compression testing machine
2. Measurement of displacement
3. Measurement of force
4. Calibration
5. Instruments for measuring the dimension of the test specimens

Test specimens

The test specimen was prepared based on the standards EN IOS 844.

Compression strength and corresponding relative deformation

Compression strength

$$\sigma_m = 10^3 \times \frac{F_m}{A_0} \tag{1.1}$$

Relative deformation

$$\varepsilon_m = \frac{x_m}{h_0} \times 100 \tag{1.2}$$

Compressive stress at 10%relative deformation

$$\sigma_{10} = 10^3 \times \frac{F_{10}}{A_0} \tag{1.3}$$

Compressive modulus of elasticity

$$E = \sigma_e \times \frac{h_0}{x_e} \tag{1.4}$$

and

$$\sigma_e = 10^3 \times \frac{F_e}{A_0} \tag{1.5}$$

where:

F_m is the maximum force reached, in newtons;

A_o is the initial cross-sectional area, in square meters, of the test specimen;

x_m is the displacement in mm corresponding to the maximum force reached;

h_0 is the initial thickness, in mm of the test specimen;

F_{10} is the force, in newtons, corresponding to a relative deformation of 10%;

A_0 is initial cross sectional area, in square meters;

F_e is the force at the end of the conventional elastic zone in newtons;

x_e is the displacement at f_e in mm;

Compressive strength is calculated at maximum load or at 10% deflection, whichever occurs first. All standards will give a comparable result. Independent of specimen configuration.

Compression moulding is calculated from the linear part of the load-displacement curve in the elastic region. Displacement or strain can be measured in three ways; from the machine drive system direct measurement on the plats or direct measurement on the specimen.

The first method does correct for deflection in the machine loading system. The first and second does not correct for the cut open surface cell of the specimen. This is weaker than close cells. Both increase the displacement, thus decreasing the modulus. Only the direct measurement on the specimen with an extensometer results in a correct modulus. In addition the relation between specimen area and height.

1.5.3. Tensile test

Most sandwich constructions are loaded in tension perpendicular to the panel, which is through the thickness direction of the foam. This limits the number of tests standards to be used since the core thickness is typical. Tensile strength is calculated at maximum load, which normally occurs when the specimen breaks. Displacement, or strain, is measured by direct measurement on the specimen with an extensometer. Tensile modulus is calculated from the steepest part of the load-displacement curve in the elastic region. As for compressive strain, displacement is allowed to be measured from the machine movement, but this will increase displacement, that decreases the modulus as describes above.

Apparatus [27]

Testing machine
Speed testing
Grips
Load indicator
Extensometer

Calculation

Stress calculation

$$\sigma = \frac{F}{A} \qquad (1.6)$$

Strain calculation

$$\varepsilon = \frac{\Delta L_0}{L_0} \tag{1.7}$$

$$\varepsilon = 100 \times \frac{\Delta L_0}{L_0} \tag{1.8}$$

The value of nominal tensile strain, shall be calculated on the basis of the initial distance between the grip:

$$\varepsilon_t = \frac{\Delta L}{L} \tag{1.9}$$

$$\varepsilon_{t(\%)} = 100 \times \frac{\Delta L}{L} \tag{1.10}$$

Modulus calculation

$$E_t = \frac{\sigma_2 - \sigma_1}{\varepsilon_2 - \varepsilon_1} \tag{1.11}$$

Poisson’s ratio

$$\mu_{n= -\frac{\varepsilon_n}{\varepsilon}} \qquad (1.12),$$

where

σ	is the tensile stress value in (MPa);
F	is the measured force concerned, in N;
A	is the initial cross-sectional area of the specimen, in square millimetres;
ε	is the strain value in question, expressed as a dimension less ratio or in percentage;
L_0	is the gauge length of specimen, expressed in mm;
ΔL_0	is the increased length between the gauge marks, expressed in mm;
ε_t	Nominal tensile strain expressed as a dimensionless ratio or percentage, %;
L	initial distance between grips, expressed in mm;
ΔL	Increase of the distance between grips, expressed in mm;
E_t	is the young modulus of elasticity, in (MPa);

σ_1 is the stress in (MPa), measured in the strain value $\varepsilon = 0.0005$;

σ_2 is the stress, in (MPa), measured in the strain value $\varepsilon = 0.0025$;

μ_n is the Poisson ratio, expressed as a dimensionless ratio with n = b (width) or h (thickness) indicates the nominal direction chosen;

ε is the strain at longitudinal direction;

ε_n is the strain at normal direction, with n=b or h;

1.5.4. Flexural Test

Flexure-testing sandwich panels, when testing solid laminates the support and loading cylinders usually have relatively small diameters. As discussed above, sandwich specimens are typically supported and loaded as wide flat plates. While the ASTM standards permit to use the steel cylinders, it is noted that there is a greater risk of local specimen crushing because of the more concentrated loading induced by a cylinder.

Any local crushing of the core under a face sheet, particularly the face sheet that is on the compression surface of the beam, is always a concern no matter which loading and support configurations are used. A locally deformed face sheet on the compression surface of a flexure specimen could fail prematurely by local bending or buckling. For this reason, the ASTM standards for sandwich panel testing specify not only flat support and loading surfaces but thick rubber pads between the support and loading flats and the specimen as well as shown in Fig 1.20. This further relieves local stress concentrations and, thus, reduces the occurrence of local face sheet damage.

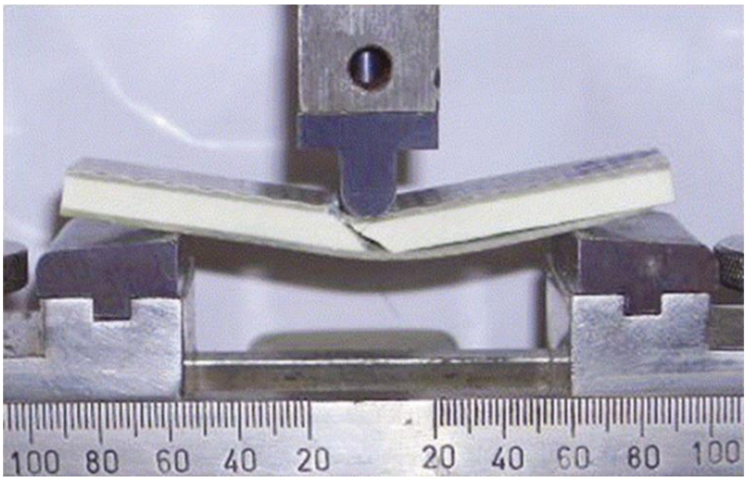


Fig 1. 20: Flexural tests [28]

Apparatus [29]

Test machine

1. General
2. Speed of the testing
3. Loading member and supports
4. Loading deflection indicators
5. Micrometres and gauges

(i) Micrometre
(ii) Vernier calliper

1. The speed can be calculated from the following equation:

$$V = \frac{\varepsilon' L^2}{6h} \text{ (3- Point)} \tag{1.13}$$

$$V = \frac{\varepsilon' L^2}{4.7h} \text{ (4- Point)} \tag{1.14}$$

2. The flexural stress σ_f is given by the following equation:

$$\sigma_f = \frac{3FL}{2bh^2} \tag{1.15}$$

3. The measurement of flexural modulus, calculate the deflections s' and s''. Which correspond to the given values of flextural strain ε'_f = 0.0005 and ε''_f = 0.0025 by the following equation

$$s' = \frac{\varepsilon_{f'} L^2}{6h} \text{ and } s'' = \frac{\varepsilon_{f''} L^2}{6h} \tag{1.16}$$

$$E_f = \frac{L^3}{4bh^3}\left(\frac{\Delta F}{\Delta s}\right) \tag{1.17}$$

$$E_f = 500(\sigma_{f'} - \sigma_{f''}) \tag{1.18}$$

4. calculate the strain in the outer surface of the specimen as follows:

$$\varepsilon = \frac{6sh}{L^2} \tag{1.19}$$

Method B – four point flexure

1. The flexural stress σ_f is given by the following equation:

$$\sigma_f = \frac{FL}{bh^2} \tag{1.20}$$

2. For the measurement of flexural modulus, calculate the deflections $s'$and s'', which correspond to the given value of flexural strain ε'_f = 0.0005 and ε''_f = 0.0025, by the following equation:

$$s' = \frac{\varepsilon_{f'} L^2}{4.7h} \text{ and } s'' = \frac{\varepsilon_{f''} L^2}{4.7h} \tag{1.21}$$

$$E_f = \frac{0.21L^3}{bh^3}\left(\frac{\Delta F}{\Delta s}\right) \tag{1.22}$$

$$E_f = 500\left(\sigma_{f''} - \sigma_{f'}\right) \tag{1.23}$$

3. Calculating the strain in the outer surface of the specimen as follows:

$$\varepsilon = \frac{4.7sh}{L^2} \tag{1.24}$$

Where

σ_f	is the flexural stress in (MPa);
F	is the load in newton’s (N);
L	is the span, in (mm);
h	is the thickness of the specimen, in (mm);
b	is the width of the specimen, in (mm);
E_f	is the flexural modulus of elasticity , in (MPa);
Δs	is the difference in deflection between s” and s’;

ΔF is the difference in load F” and load F’ at s” and s’ respectively.

$\sigma_{f'}$ is the stress measured at the deflection s’, in (MPa);

$\sigma_{f''}$ is the stress measured at the deflection s”, in (MPa);

1.5.5. Shear strength

Principle

A test specimen consists of a strip of rectangular cross-section with different fibre oriented to the specimen axis are located in tension. To determine the shear modulus, the strain parallel and perpendicular to the specimen axis are measured [30]. Tests with specimens prepared by bonding several layers of a material appear to be the only available method at this time for determining stress strength response. Obviously, specimen preparation needs some effort and the quality of the bond may affect the results in some cases.

Test specimens

The test specimen shall be right parallelepipeds of the following dimension:

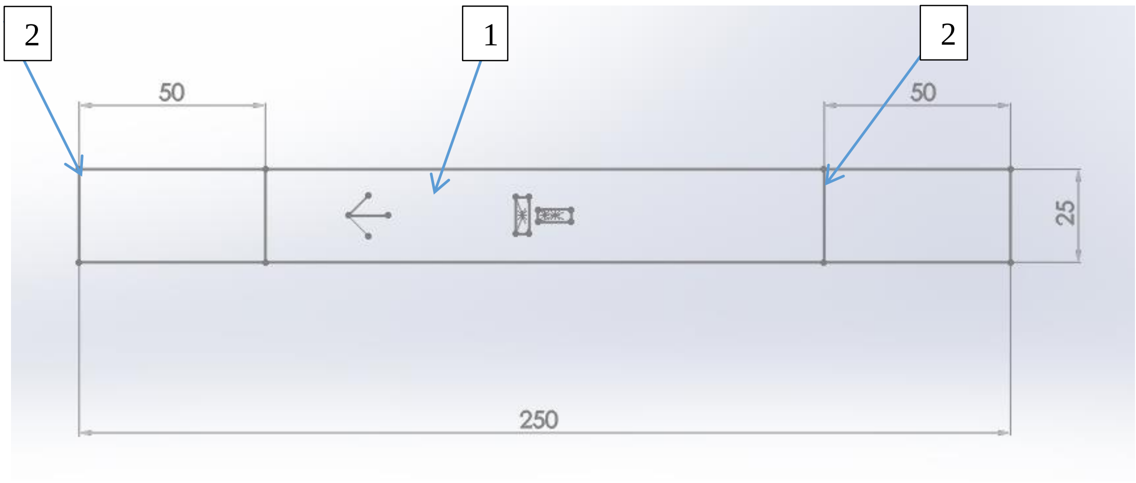


Fig 1.21. Fibre-reinforced plastic composite specimen showing fibre axes (1. Strain gauges, 2. Tab

Adhesive

The adhesive used in the metal support to the test specimen shaft be such that the shear strength and modulus of the adhesive film are significantly greater than that of the cellular material under test. So as to ensure that ultimate failure in the cellular material rather than at the adhesive interface. The adhesive shall also be compatible with the material under test.

International standard

In-plane shear stress τ_{12} ;

In-plane shear strength $\tau_{12\mathrm{M}}$;

Shear strain γ_{12} ;i .e. ($\varepsilon_{\mathrm{x}} - \varepsilon_y$).

In-plane shear modulus G_{12} ; shear stress difference ($\tau_{12''} - \tau_{12'}$).

Calculation

1. Calculate the in plane shear stress τ_{12} , in MPa

$$\tau_{12} = \frac{F}{2bh} \quad (1.25)$$

2. Calculate the in –plane shear strength $\tau_{12\mathrm{M}}$, in MPa

$$\tau_{12M} = \frac{F_m}{2bh} \tag{1.26}$$

3. Calculate the shear strain γ_{12}

$$\gamma_{12} = \varepsilon_{\mathrm{x}} - \varepsilon_y \tag{1.27}$$

4. Calculate the in- plane shear modulus G_{12} ,in MPa

$$G_{12} = \frac{\tau_{12''} - \tau_{12'}}{\gamma_{12''} - \gamma_{12'}} \tag{1.28}$$

5. Calculate the arithmetic mean of the individual determinations and, if required. The standard deviation and the 95% confidence interval of the mean value using the procedure given in ISO 2602.

Where

F	is the instantaneous, in newtons;
b	is the width;
h	is the thickness;
ε_x	is the strain the direction parallel to the specimen axis;
ε_{12}	is the strain the direction perpendicular to the specimen axis;
τ_{12}	is the shear stress at Shear strain;
τ_{12}	is the shear stress at Shear strain;

1.6. MODELLING OF SANDWICH STRUCTURES

One of the most important and exciting areas of composites research is the development of modelling techniques to predict the response of composite materials. Modelling provides the opportunity both to understand better how composites behave in different situations and to produce the materials with higher efficiency for particular industrial applications.

The mechanics of composite can be divided into three types namely theoretical modelling applies and computational modelling. The theoretical models are created using the basic principle and theoretical knowledge to develop the mathematical models for a scientific and engineering applications. The computational modelling was developed to solve the specific problems by simulation of numerical models.

The specific problem in the engineering applications are analysed in two different way firstly static analysis other is dynamic analysis. Theses analysis are performed in linear are nonlinear analysis. Static analysis and dynamic analysis differ with time. Dynamic analysis is calculated with respected to time consideration. In static analysis, there is no obligation for time dependency.

In this research static analysis is used to analyse the behaviour of the sandwich composite. There are various method are used for modelling such as;

a) Finite Element Method (FEM)

b) Boundary Element Method (BEM)

c) Finite Difference Method (FDM)

d) Finite Volume Method (FVM)

e) Spectral Method

f) Mesh-Free Method

For numerical analysis of honeycomb sandwich structure, even though various modelling approaches are developed. The finite element analyse is one of the means used to find the approximation of the global behaviour of the sandwich panels. [33]

The modelling of the composite material is complex when compared to traditional engineering materials. The strength and stiffness properties of the composite depend on the fiber volume and the respective properties of the composing materials. When the number of layup changes also will increase the complexity in the analysis of composite structures.

For the finite element analysis of the composite sandwich structure, ANSYS 14.5 was used. The composite materials are a bitten complex to model due to their verity of orthotropic properties. So during the material modelling, the suitable element type should be selected and the number of the layer should be defined to each facesheet laminates. In this research two material models were created one was facesheet and another was the sandwich panel with honeycomb core. The material models were calibrated using the material properties obtained experimentally, the facesheet was verified using tension test simulation and the sandwich panel was verified using three points bending simulation. Theses verifies material models were used for the investigation.

Summary of literature review

Composite materials have now found applications in commercial industries. In various cases, using composite is more efficient. Sandwich FRP composites have emerged as important material because of their high specific strength and high specific stiffness, light weight, high fatigue resistance compared to common metallic alloys. Fiber reinforced plastic facesheets are more common in facesheet materials used in sandwich composites used in industrial applications. There is a variety of core material available in the industrial market, but honey honeycomb core is used for their specific mechanical properties suitable for industrial applications and manufacturing conditions. Sandwich of fiber reinforced facesheets and honeycomb core can be manufactured in a number of methods such as hand layup, resin transfer moulding, vacuum bagging, heated press. There many problems in manufacturing the sandwich composites based on the structural geometries were it should fulfil the requirement of light weight, high strength and stiffness properties and cost economical. So to find the optimal geometrical structure of sandwich composite with good mechanical properties. The static analysis was performed, were the problems can be seen in numerical models of finite numbers and degrees of freedom. So, finite element analyse was performed which is one of the means used to find the approximation of the global behaviour of the sandwich panels. Various experimental testing methods such as compression, tensile, flexural, shear test were used to find the basic mechanical properties of composite creating the models. To sum up the review the problem of finding the optimal thickness of the facesheet of the sandwich structure at which high strength and stuffiness properties are obtained and suitable for manufacturing in an economical cost of the material.

2. EXPERIMENTAL AND THEORETICAL ANALYSIS OF LAMINAR PROPERTIES OF FRP FACESHEET

2.1. Materials and geometrical description of the laminate construction

The glass fiber reinforced plastic laminate was use for the experimental investigation. FRP laminate was made up of wound glass fibre reinforced with polyvinylester resin. The geometrical description of the experimental specimen was thickness 3.5 mm and length of the laminate sample were 200 mm and width 25.5 mm. In order to find the mechanical properties of the laminate experimental testing were performed according to the standards.

2.2. Experimental setup

The experimental testing of the FRP laminate was performed according to the standards of EN ISO 527-4 Plastics. In order to determine the tensile properties and test condition of isotropic fiber- reinforced plastic composites at the temperature of 20°C, the test was carried out at the test rate 2 mm/min and the specimens prepared from the tank diameter of 1.8m shown in Fig 2.1.

Instruments used

a. Force transducers 100kN±200N, 10kN±10N,
b. Displacement transducer 20±0,04mm,
c. Extensometer base 50, range ±2,5mm,

(a) (b)

Fig 2.1. Tensile testing of FRP specimen

This table represents the experimental results of glass fiber reinforced composite face sheet specimen of fiber orientation in 0˚. The maximum force, young's modulus and maximum stress are calculated from the experiment values.

Table 2.1. Test result of sample 1 (0˚)

	Breath mm	Thickness mm	Fmax kN	E GPa	σ_{max} MPa
1-0-T	25.6	3.4	21.3	31.6	245.8
2-0-T	25.4	3.5	30.7	22.8	345.6
3-0-T	25.8	4.2	58.2	31.2	537.2
4-0-T	25.6	3.6	52.8	26.7	573.9
7-0-T	25.2	3.4	24.5	23.1	286.2
8-0-T	25.2	3.3	39.4	28.9	474.6
9-0-T	25.9	3.6	22.5	30.1	241.6
Average				27.8	386.4
Standard deviation				3.7	140.3
confidence				2.7	103.9

This table represents the experimental results of glass fiber reinforced composite face sheet specimen of fiber orientation in 30˚. The maximum force, young's modulus and maximum stress are calculated from the experiment values.

Table 2.2. Test result of sample 2 (30˚)

	Breath mm	Thickness mm	F_{max} kN	E GPa	σ_{max} MPa
1-30-T	25.9	3.6	15.5	22	166.7
2-30-T	25.9	3.6	15.7	19.4	169
3-30-T	25.9	4.1	16.2	22	153.5
4-30-T	25.9	4.1	17.3	18.8	163.4
5-30-T	25.1	3.6	16.1	21.6	179
Average				20.76	166.32
Standard deviation				1.538831	9.23293
confidence				1.139961	6.839725

This table represents the experimental results of glass fiber reinforced composite face sheet specimen of fiber orientation in 60˚. The maximum force, young’s modulus and maximum stress are calculated from the experiment values

Table 2 3. Test result of sample 3 (60˚)

	Breath mm	Thickness mm	Fmax kN	E GPa	$\sigma_{\max}$ MPa
1-60-T	25.5	3.8	1.66	7.5	17.2
2-60-T	25.1	4.1	1.72	7.8	16.7
3-60-T	25.9	3.8	1.77	7.3	17.8
4-60-T	25.7	4.9	1.68	5.2	13.3
5-60-T	25.6	3.7	1.62	6.5	17.1
Average				6.86	16.42
Standard deviation				0.935094	1.59925
confidence				0.692714	1.184719

This table represents the experimental results of glass fiber reinforced composite face sheet specimen of fiber orientation in 60˚. The maximum force, young’s modulus and maximum stress are calculated from the experiment values.

Table 2.4. Test result of sample 4 (90˚)

	Breath mm	Thickness mm	Fmax kN	E GPa	$\sigma_{\max}$ MPa
1-90-T	25.6	3.4	1.34	0.01	15.5
2-90-T	25.7	4.9	1.24	0.007	9.8
3-90-T	25.7	3.3	1.17	0.01	13.8
4-90-T	25.7	3.4	0.55	0.01	6.4
5-90-T	25.3	3.4	0.71	0.01	8.2
6-90-T	25.7	4.8	1.46	0.008	11.91
Average				0.009167	10.935
Standard deviation				0.001329	3.444786
confidence				0.000985	2.551886

2.3. Theoretical calculation laminate properties

The successful design of a structure requires high efficient and safe use of materials. So firstly theoretical calculation should be developed to compare the material properties. Initially a laminate is defined as organized stack of uni-directional or bi-directional composite plies. During the stacking of plies each ply id defined by fiber direction as shown in Fig 2.2

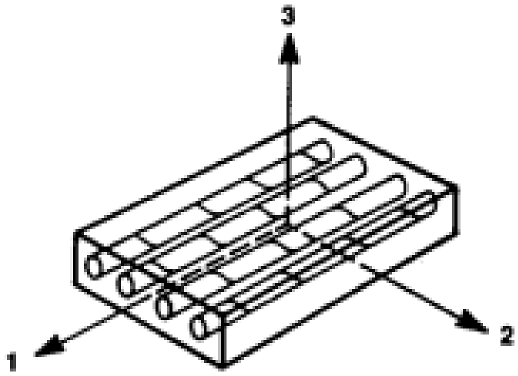


Figure 2.2. Material coordinate system [6]

While the whole laminate is defined according to this x-y-z coordinate system, in every individual ply of the laminate, the material properties of the composite material should be defined.

Mechanical Elasticity

E_1 E_2

ν_{12}

$\nu_{21} = E_2 * \frac{\nu_{12}}{E_1}$ (2.1)

$\varepsilon_{max=0.0025/1.25}$ Permissible deformation 0.25% EN 13121-2 7.3 item requirement

Glass fiber orientation angles:

$\alpha_1 = \theta$ $\alpha_2 = \theta$ $\alpha_3 = \theta$

$c_{1} = \cos(\alpha_{1*deg})$ $c_{2} = \cos(\alpha_{2*deg})$ $c_{3} = \cos(\alpha_{3*deg})$

$s_{1} = \sin(\alpha_{1*deg})$ $s_{2} = \sin(\alpha_{2*deg})$ $s_{3} = \sin(\alpha_{3*deg})$

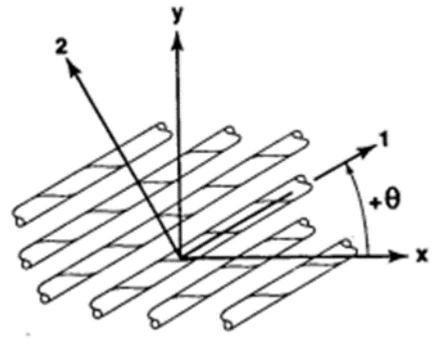


Fig 2.3. Positive rotation of principle material axis from x-y [6]

n_1 The number of layers with an angle α_1

n_2 The number of layers with an angle α_2

n_3 The number of layers with an angle α_3

$$n = n_1 + n_2 + n_3 \tag{2.2}$$

Thickness, mm, 1.5mm when oriented at 0 degrees and oriented only 0.9mm when the circumferential direction

$t_1 = n_1 * 1$ $t_2 = n_2 * 1$ $t_3 = n_3 * 1$

$$t_{tot} = t_1 + t_2 + t_3 \tag{2.3}$$

$z_1 = \frac{n_1}{n}$

$z_2 = \frac{n_2}{n}$

$z_3 = \frac{n_3}{n}$

$$z = z_1 + z_2 + z_3 \tag{2.4}$$

Condition must be satisfied $z_1 = z_1$ $z_2 = z_2$ $z_3 = z_3$

The matrix is 6×6 matrix that serves as a connection between the applied loads and the associated strains in the laminate. It essentially defines the elastic properties of the entire laminate.

$s_{11}=\frac{1}{E_1}$

$s_{22}=\frac{1}{E_2}$

$s_{66}=\frac{1}{G_{12}}$

$s_{12}=\frac{-\nu_{12}}{E_1}$

$s_{21}=\frac{-\nu_{21}}{E_2}$

$s_{16}=0$ $\qquad s_{61}=s_{16}$

$s_{62}=s_{16}$ $\qquad s_{26}=s_{16}$

Calculating the reduced stiffness matrix s for the material used in the laminate. This stiffness matrix describes the elastic behaviour of the ply in plane load.

$$S = \begin{bmatrix} s_{11} & s_{12} & s_{16} \\ s_{21} & s_{22} & s_{26} \\ s_{61} & s_{62} & s_{66} \end{bmatrix} \tag{2.5}$$

$$Q=S^{-1} \qquad R=\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2.6}$$

$$T_1 = \begin{bmatrix} {c_1}^2 & {s_1}^2 & 2*s_1*c_1 \\ {s_1}^2 & {c_1}^2 & -2*s_1*c_1 \\ -s_1*c_1 & s_1*c_1 & {c_1}^2-{s_1}^2 \end{bmatrix} \tag{2.7}$$

$$T_1 = \begin{bmatrix} {c_1}^2 & {s_1}^2 & 2*s_1*c_1 \\ {s_1}^2 & {c_1}^2 & -2*s_1*c_1 \\ -s_1*c_1 & s_1*c_1 & {c_1}^2-{s_1}^2 \end{bmatrix} \tag{2.8}$$

$$T_1 = \begin{bmatrix} {c_1}^2 & {s_1}^2 & 2 * s_1 * c_1 \\ {s_1}^2 & {c_1}^2 & -2 * s_1 * c_1 \\ -s_1 * c_1 & s_1 * c_1 & {c_1}^2 - {s_1}^2 \end{bmatrix} \tag{2.9}$$

Calculating the A1, A2, A3 matrixes using the following equation.

$$A_1 = {T_1}^{-1} * Q * R * T_1 \ * R^{-1} \tag{2.10}$$

$$A_2 = {T_2}^{-1} * Q * R * T_2 \ * R^{-1} \tag{2.11}$$

$$A_3 = {T_3}^{-1} * Q * R * T_3 \ * R^{-1} \tag{2.12}$$

$$A = z_{1*}A_1 + z_{2*}A_2 + z_3 * A_3 \tag{2.13}$$

a = A^{-1}

$$a = \begin{bmatrix} a_{(0,0)} & a_{(0,1)} & a_{(0,2)} \\ a_{(1,0)} & a_{(1,1)} & a_{(1,2)} \\ a_{(2,0)} & a_{(2,1)} & a_{(2,2)} \end{bmatrix} \tag{2.14}$$

$$E_{xx} = \frac{1}{a_{(0,0)}} \quad E_{yy} = \frac{1}{a_{(1,1)}} \quad G_{xxyy} = \frac{1}{a_{(2,2)}}$$

$$\nu_{xx} = \frac{-1 * a_{(0,1)}}{a_{(0,0)}} \qquad \nu_{yy} = \frac{-1 * a_{(0,1)}}{a_{(1,1)}} \qquad \nu_{xxyy} = \frac{-1 * a_{(0,1)}}{a_{(2,2)}}$$

E_1 - longitudinal tensile modulus;

E_2 - transverse tensile modulus;

G - in- plane shear modulus;

ν - Poisson's ratio;

S_S - in-plane shear strength;

t - Laminate thickness;

3. MATERIAL MODELLING AND ANALYSIS

3.1. Materials and finite element modelling of facesheet model

Sandwich panels consist of two thin facesheets covering the light weight core. For numerical analysis of honeycomb sandwich structure, various modelling approaches are developed but finite element method is one of the means used to find the global characters of the material. Firstly facesheets of the honeycomb core sandwich panels were modelled.

The facesheet was fabricated from glass fiber R25H made of advanced glass and designed for filament winding processes and polyvinylester resin. In order to find the mechanical properties of the FRP facesheets various testing were performed according to standards ISO 527, ISO 604, ISO14129. These experiments were performed in room temperatures and rate of loading were 2mm/min. the obtained mechanical properties are shown in Table 5.

Table 3.1. Mechanical properties of FRP facesheet

Mechanical properties	**Value**	**Units**
Tension strength	645	MPa
Compression strength	248	MPa
Longitudinal young's modules E_1	37.5	GPa
Transverse young's modules E_2	7.32	GPa
Poisson's ratio v_{12}	0.28	-
Poisson's ratio v_{21}	0.05	-
Shear modules G_{12}	3.79	GPa
In plain shear strength, S_{12}	23.0	MPa

The laminate code was [±65/90], the thickness of the plies were 0.9 mm and 0.75 mm for ±65 and 90 plies, respectively. The total thickness was 2.4 mm and the fiber volume was 43%. The mechanical properties for the material model were used from the experimentally obtained data. The facesheet was modelled using shell element. In order to reduce the computational time for large models shell composite elements with a single layer, assumptions were used to model the facesheet material models. The shell is assumed to be made up of an equivalent single homogeneous layer. The material models were created using finite element modelling in ANSYS 14.5 as shown in Fig 3.1.

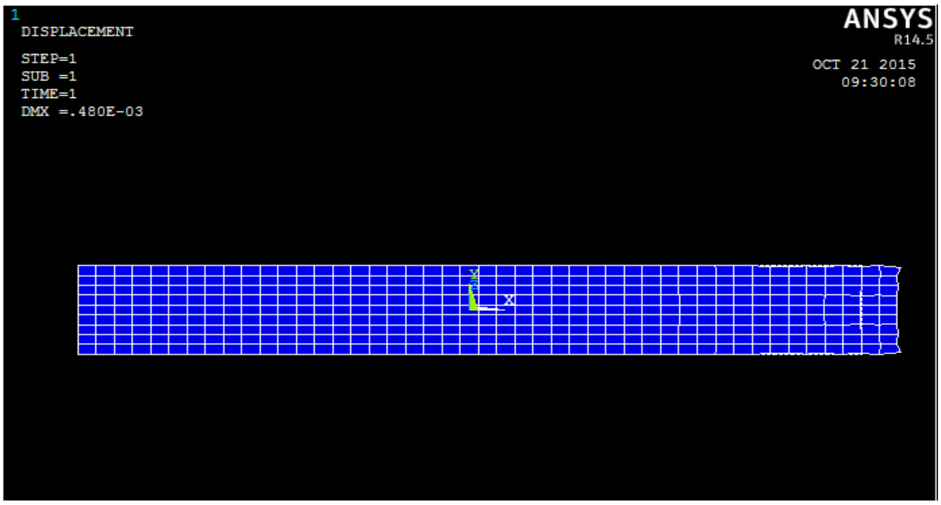


Fig 3.1. Finite element model of facesheet

3.2. Verification of numerical model by tensile test simulation

The quasi-static test was simulated by applying a constant load of 100 mm/s. The material model not only contains experimentally measured physical properties, but also the software specific parameters which are usually found in material model calibration used to concurrent between the experimental simulation shown in Fig 3.2.

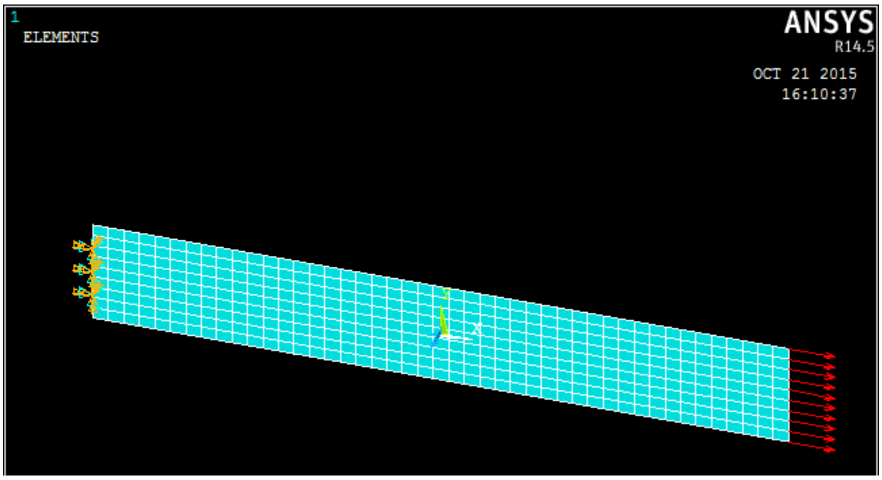


Fig 3.2. Tensile test simulation

To verify the finite element material model of the FRP facesheet and also to obtain the specific software parameters, a tension test was performed as shown in Fig 3.3. Initially verification of the numerical model of FRP facesheet by simulating the tensile test was performed. The mechanical properties use to calibrate the material model is shown in Table 3.1. The linear dependence curve shows a good agreement with experimental stress –strain curve as shown in Graph 3.1.

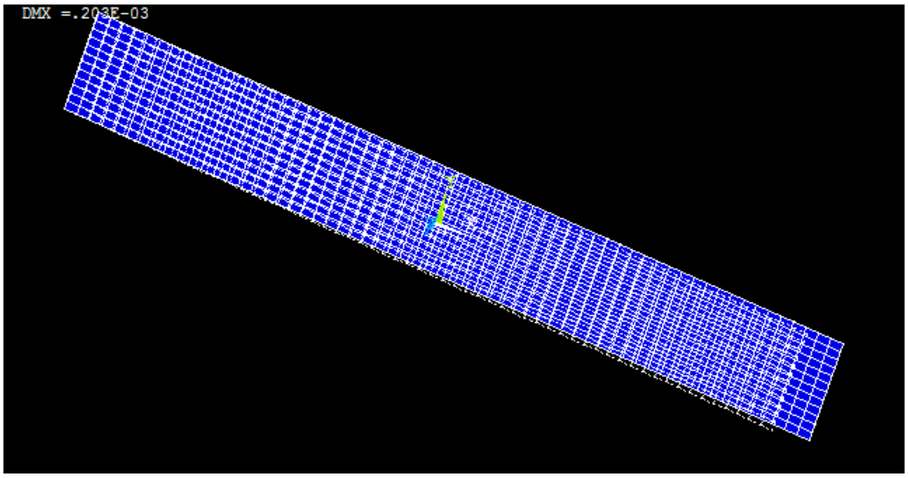
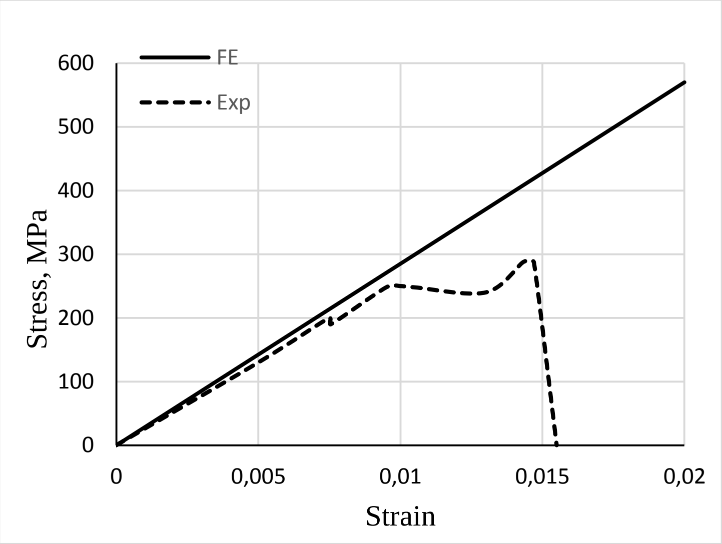


Fig 3.3. deformed model of tensile simulation



Graph 3.1. Tension stress – strain curve of FRP composite

3.3. Material and Finite element modelling of honeycomb core sandwich

The sandwich structure presented in Fig 3.4 was used for the investigation. In order to find the mechanical properties of the sandwich materials various tests were carried out according to the standards. For facesheets ISO 527, ISO 604, ISO14129 and honeycomb core ISO 844, ISO 1922 were used. The obtained mechanical properties are presented in Table 3.1 and Table 3.2

Fig 3.4. Model of sandwich with honeycomb core.1 – woven glass fibre and polyvinylester resin composite facesheet; 2 - recycled paper hexagonal honeycomb impregnated in polyvinylester resin

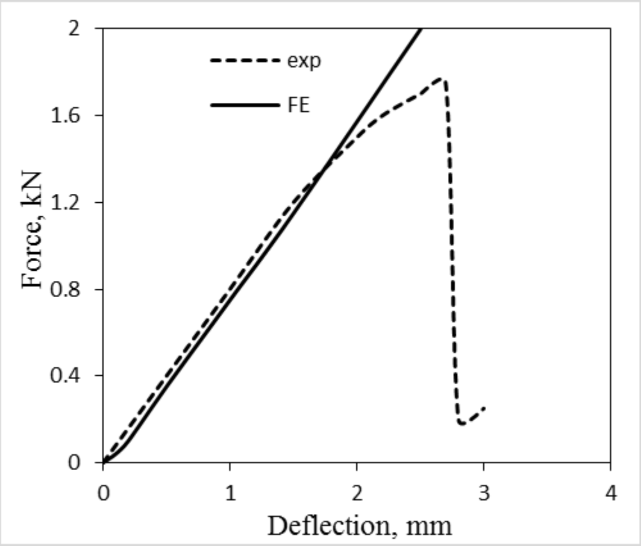
Table 3.2. Mechanical properties of the paper honeycomb core.

Mechanical properties	**Value**	**Units**
Young's modules	10	MPa
Compression strength	0.48	MPa
Shear modules	235	MPa
Shear strength	0.64	MPa

The sandwich structure with facesheets made of wounded glass fibre and polyvinylester resin and the core made of recycled paper hexagonal honeycomb impregnated in polyvinylester resin. According to experimentally obtained data, the models of honeycomb core sandwich structure (with a honeycomb) and neat FRP facesheet material (without the honeycomb) were created using finite element modelling in ANSYS 14.5. The bonding between the honeycomb core and the facesheet was modelled with a "glue" layer. The properties of the glue for the numerical model were defined as the mechanical properties of synolite 8388-P-1 resin (Young's modulus and tensile strength were 3.7 GPa and 14 MPa, respectively).

Verification of the sandwich structure model was performed by simulating three point bending test. Previously, an experimental test was carried out. The dimensions of the specimens were as follows: width 60 mm, the distance between the supports 200 mm, the thickness of the top facesheet 2.68 mm, the thickness of bottom facesheet 2.81 mm, the core thickness 10 mm and thickness of sandwich 15.5 mm.

The force versus deflection was measured during this test and the linear dependence curve of FE model shows a good agreement with experimentally obtained curve as shown in graph 3.2.



Graph 3.1. Force versus deflection curve obtained experimentally and by FE simulation

3.3.1. Model with honeycomb core and without honeycomb core

Two FE models namely honeycomb core sandwich structure (with a honeycomb) and neat FRP facesheet material (without the honeycomb) were modelled and compared by three point bending simulation as shown in Fig 3.5. This methodology was used in order to find the optimal thickness of FRP facesheets at which the high stiffness and strength properties can be obtained.

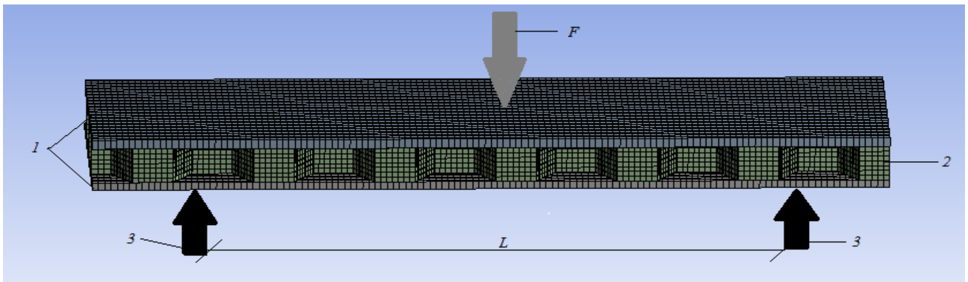


Fig 3.5. The numerical model of three point bending specimen. F ¬- force applied, 1 - facesheets, 2 - hexagonal honeycomb core, 3 - supports, L – length between the supports

Firstly a sandwich structure with two thin facesheet and thick honeycomb core in between the facesheets was modelled. The dimensions of the model were as followed: width 60 mm, the thickness of the top facesheet 2.68 mm, the thickness of the bottom facesheet 2.81 mm, the core thickness 10 mm, the sandwich thickness 15.49 mm and the laminate code was ($[\pm 65]_2$ / core /$[\pm 65/90]$).

The other model with two thin facesheets and without honeycomb core was modelled. The dimensions and the material models were same as the first model. Two models are shown in the Fig 3.6.

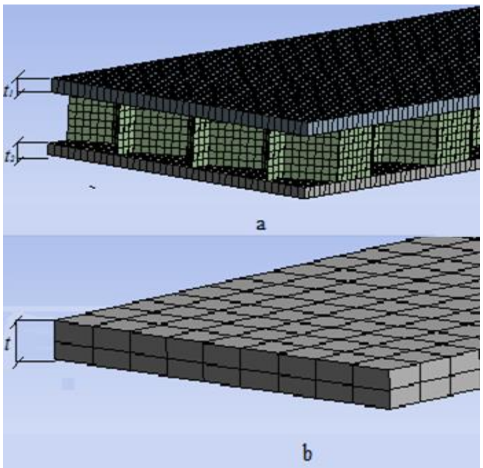


Fig 3.6. Models: (a) - model of honeycomb core sandwich composite; (b) – the model of neat FRP sandwich composite. t_1 & t_2 - thickness of top facesheet and bottom facesheet; t ($t = t_1+t_2$) – thickness of neat FRP sandwich

3.3.2. Three point bending simulation of sandwich models

Using verified model the quasi-static three point bending tests were simulated. Two FE models namely honeycomb core sandwich structure (with a honeycomb) and neat FRP facesheet material (without the honeycomb) were used in the three point bending simulation with three different distance between the supports such as 100 mm, 150 mm and 200 mm. A constant load of 800 N was applied in all simulation. This investigation was carried out in three different ways by varying the facesheet thickness. Such as $t_1 > t_2$, $t_1 < t_2$, $t_1 = t_2$ (t_1- thickness of top facesheet and t_2- thickness of bottom facesheet). The thickness of facesheet was increased step by step in every investigation and three point bending simulation was simulated as shown in Fig 3.5 for each thickness change of facesheet and the deflection at that thickness was recorded.

For both honeycomb core sandwich structure and neat FRP composite the stiffness were calculated according to the equation:

$$K = \frac{F}{y_{\max}} \tag{3.1}$$

Where K – stiffness, F – force applied, y_{max} – maximum deflection.

The maximum deflection coefficient $k_{y_{\max}}$ which can be represented as ratio of maximum deflection of neat FRP composite to the maximum deflection of honeycomb core composite structure was used:

$$k_{y_{\max}} = \frac{y_{\max_1}}{y_{\max_2}} \tag{3.2}$$

Where $y_{\max_1}$ - maximum deflection of neat FRP composite; $y_{\max 2}$ - maximum deflection of honeycomb core composite structure.

The coefficient $k_{\sigma_{\max}}$ represented the ratio of maximum stress σ_{max} of neat FRP composite to the maximum stress of honeycomb core FRP sandwich. This can be expressed as:

$$k_{\sigma_{\max}} = \frac{\sigma_{\max_1}}{\sigma_{\max_2}} \tag{3.3}$$

Where $\sigma_{\max_1}$ - maximum equivalent stress of neat FRP composite; $\sigma_{\max 2}$ - maximum equivalent stress of honeycomb core composite structure

4. RESULT OF EXPERIMENTAL AND NUMERICAL ANALYSIS

4.1. Experimental and Theoretical properties of FRP laminate facesheet

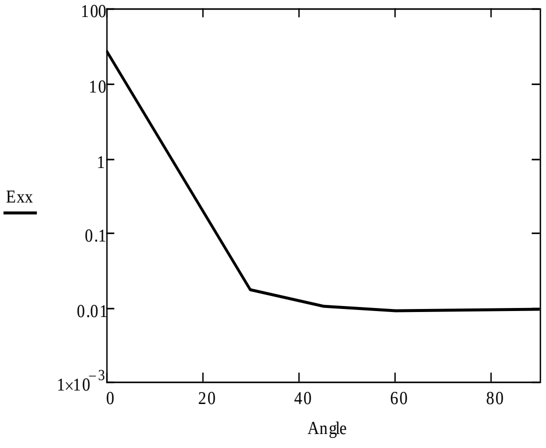
The sandwich panels were tested experimentally and the material properties were obtained and the laminar theory was used to calculate the theoretical properties and it was used to and it was used to compare the obtained effective elastic modulus of the of FRP facesheet. The results are shown in Table 4.1.

Table 4.1. Comparison of general mechanical characteristic of FRP

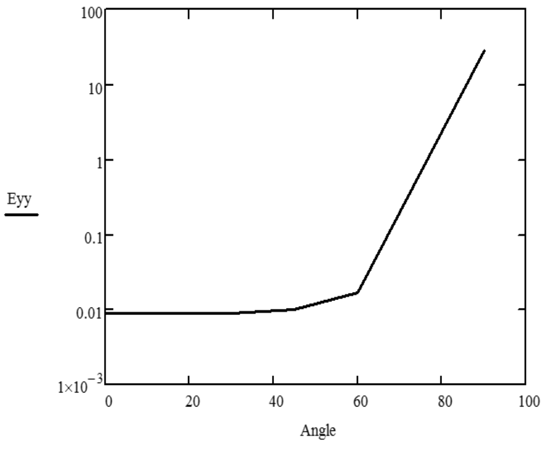
Effective modules E_y (GPa)		
Angle in degree	experimental	Laminate theory
0 °	27.8	27.77
30°	20.6	19.8
60°	6.86	6.73
90 °	0.009167	0.0092

It clear that results obtained from the theoretical calculation show a closer agreement with experimental results. Using this experimentally obtained data, the numerical FE model of facesheet was designed. The three point bending test was performed to verify sandwich structure. The experimentally obtained data was used to create a numerical model.

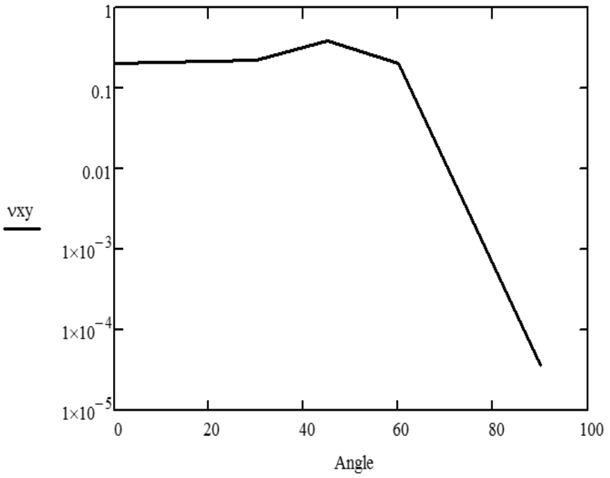
The general mechanical characteristics of the facesheet material were theoretically investigated using laminate theory. A methodology used to investigate the laminates by properties changes depending on the change of fiber orientation angle. The obtained data is plotted in the graph with respected to angles. As shown in the bellow graphs.



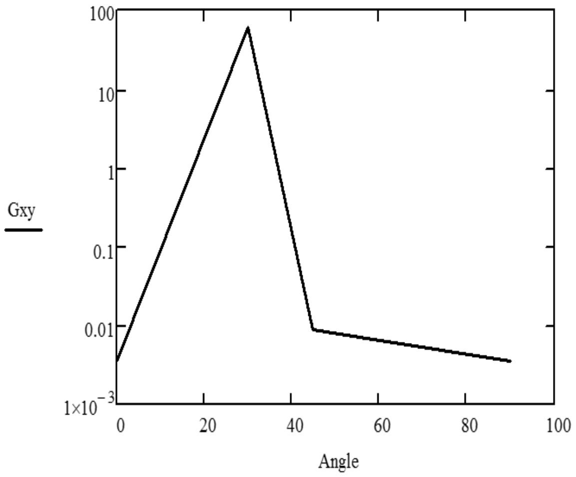
Graph 4.1. Elastic modulus in direction-x as a function of the angle of lamina



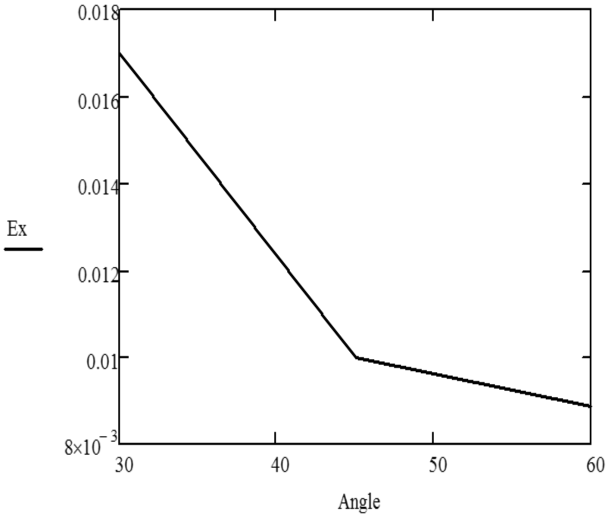
Graph 4.2. Elastic modulus in direction-y as a function of the angle of lamina



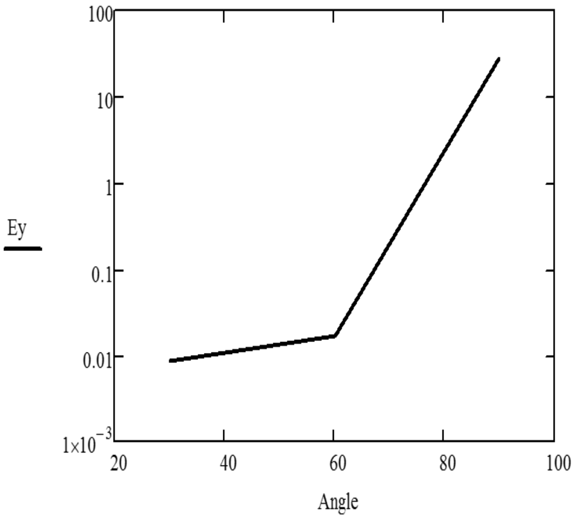
Graph 4.3. Poisson’s ratio ν_{xy} as a function of the angle of lamina



Graph 4.4. Elastic modulus in direction-x as a function of the angle of laminate



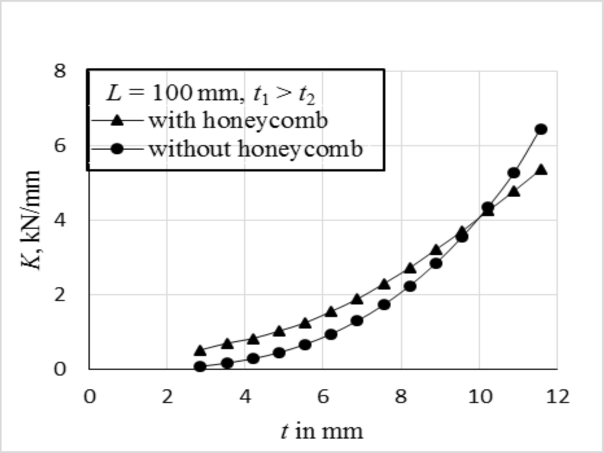
Graph 4.5. Elastic modulus in direction-x as a function of the angle of laminate



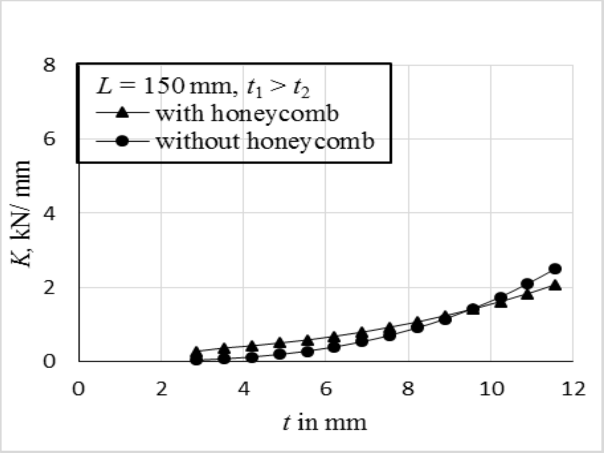
Graph 4.6. Elastic modulus in direction-y as a function of the angle of laminate

4.2. Influence of FRP Thickness on stiffness of sandwich structure

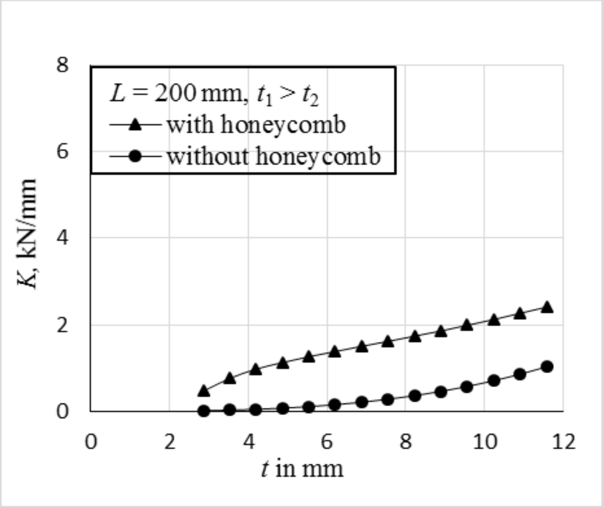
The stiffness variation influenced by the thickness of FRP was calculated for both honeycomb core sandwich structure and neat FRP. The stiffness increases as the thickness of the FRP increases in all the cases. For lower thickness value, the stiffness for honeycomb sandwich structure is higher than neat FRP composite. At a particular thickness value, stiffness of both honeycomb sandwich structure and neat FRP are same, but that particular point differs depending on the thickness orientation and distance between the supports. For $t_1 > t_2$ when L = 100 mm the value is $t = 9 – 10$ mm, when L = 150 mm the value is $t = 10 – 11$ mm, when L = 200 mm twice higher the other thickness.



(a)

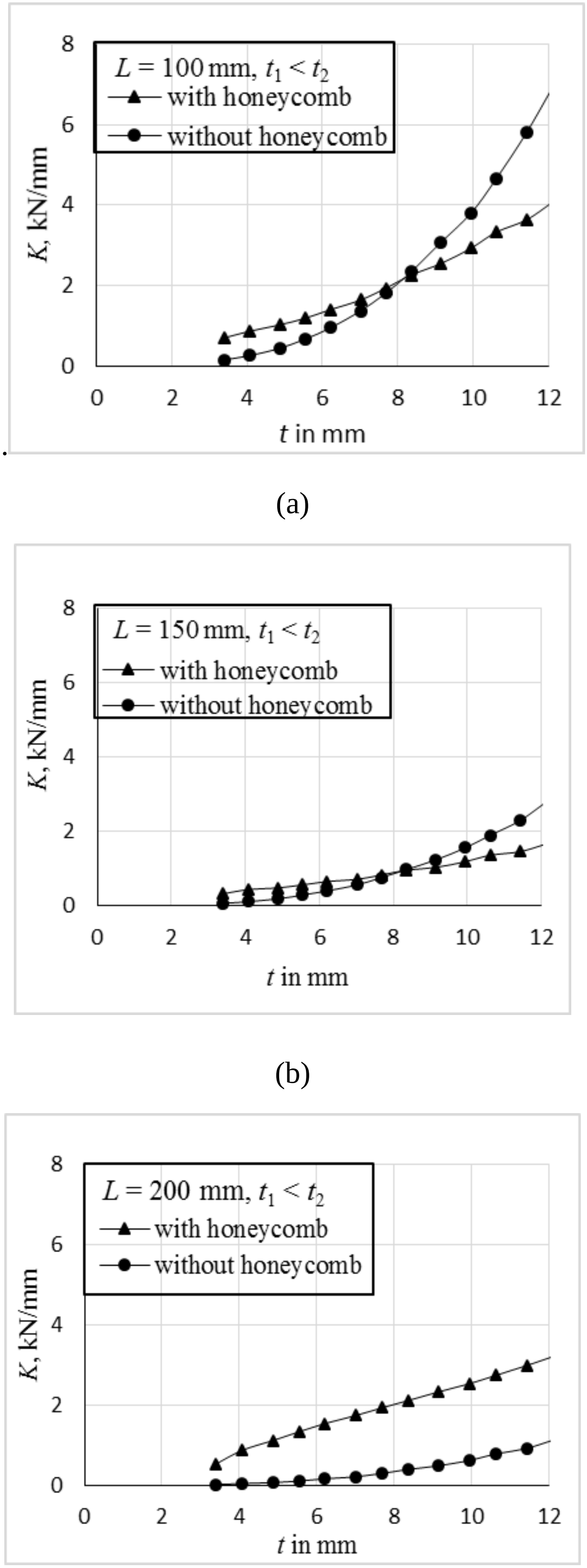


(b)



(c)

Graph 4.7. Influence of FRP thickness t on stiffness K: a, b, and c – where the top facesheet thickness t_1 is greater than bottom face sheet t_2 lengths between supports respectively 100, 150, 200 mm.

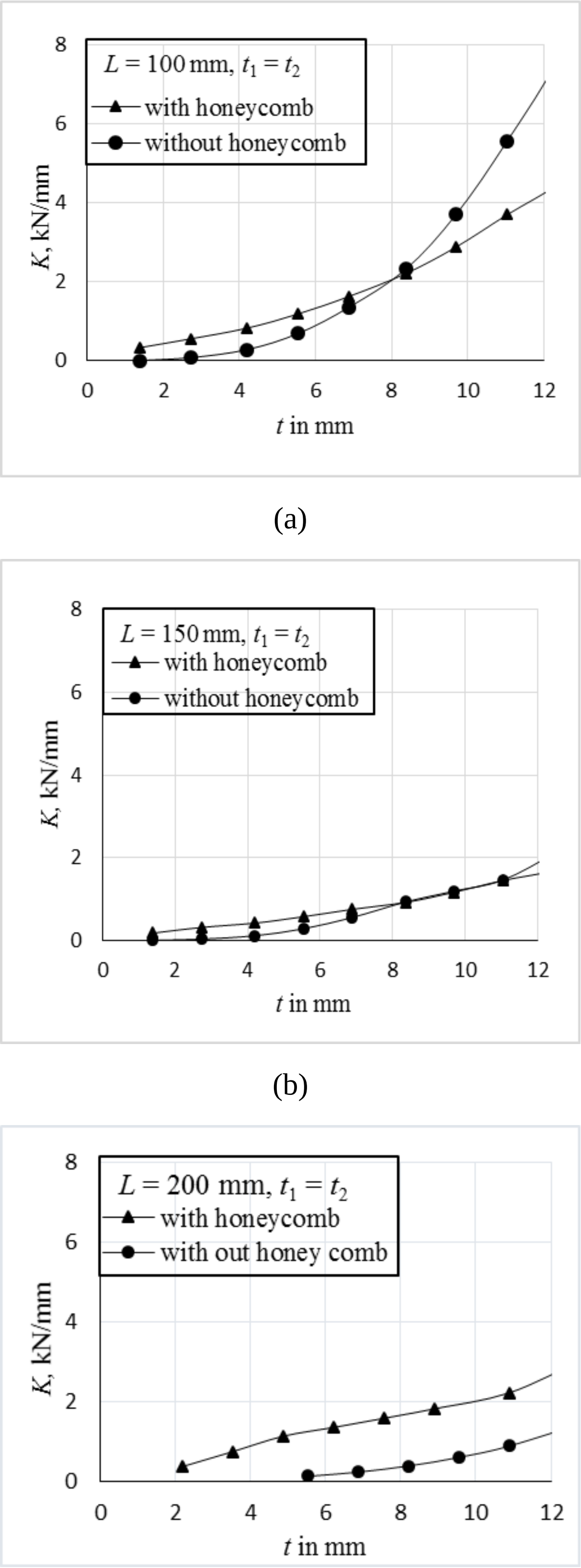


(a)

(b)

(c)

Graph 4.8. Influence of FRP Thickness *t* on stiffness *K*: a, b, and c – where the top facesheet thickness t_1 is lesser than bottom face sheet t_2 lengths between supports respectively 100, 150, 200 mm.



(a)

(b)

(c)

Graph 4.9. Influence of FRP Thickness t on stiffness K: a, b, and c – where the top facesheet thickness t_1 is equal to bottom face sheet t_2 lengths between supports respectively 100, 150, 200 mm.

For $t_1 < t_2$ when L = 100 mm the value is t = 7 – 8 mm, when L = 150 mm the value is t = 8 – 9 mm, when L = 200 mm the value is twice higher the other thickness. For $t_1 = t_2$ when L=100 mm the value is t = 8 – 9 mm, when L = 150 mm the value is t = 9 – 10 mm, when L = 200 mm the value is also double. Below this thickness value, the stiffness of the honeycomb core sandwich structure is higher than the neat FRP. In the same case above this thickness value, the stiffness of the neat FRP is higher than the honeycomb core sandwich structure. The graph clearly represents that stiffness value of L = 100 mm higher than L = 150 mm that is more or less double the value also in L = 200mm.

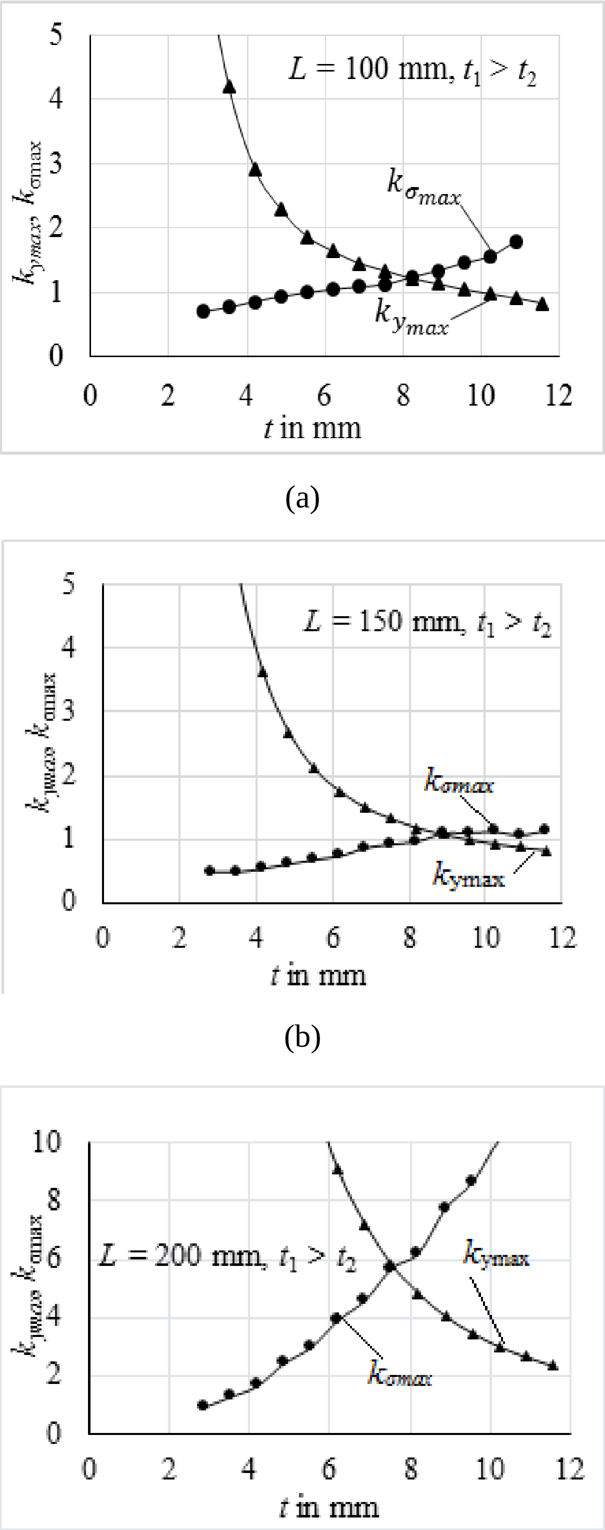
4.2.1. Influence of FRP Thickness on coefficient of maximum deflection and equivalent stress

By only comparing the optimal thickness, the stiffness of the composite is not so clear because of the same value of stiffness can be obtained from constant F and different y_{max} values. So the influence of thickness separately on y_{max} and σ_{max} were investigated.

The coefficient $k_{y_{\max}}$ and $k_{\sigma_{\max}}$ are defined by y_{max} and σ_{max} values, which is obtained from different thickness and length between the supports. It is clear that the deflection decreases when the thickness of the FRP increases and the distance between the support decreases. The effects of the maximum deflection value of honeycomb core composite were found only when the thickness of FRP is lower and distance between the supports is increased.

In case of neat FRP composite, it has the minutiae stiffness in the lower thickness values so coefficient $k_{y_{\max}}$ cannot be calculated

In contrast for thickness t equal to 5 mm (at this value honeycomb height is 80% of the total composite thickness [31, 32]). The deflection of the honeycomb core FRP composite is close to 2.1, 2.6, and 14 times lower than the neat FRP composite in all three conditions as the distance between composite are 100, 150 and 200.

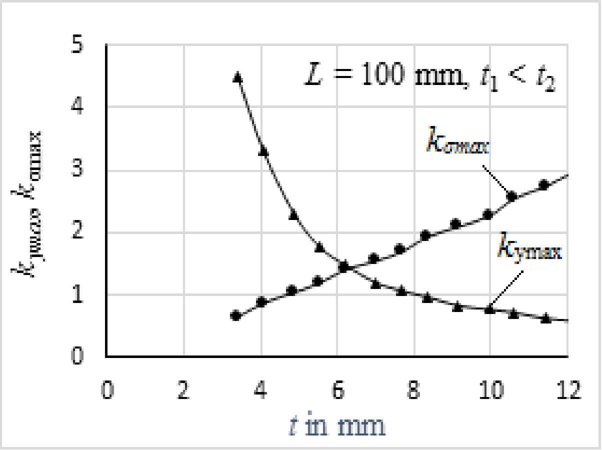


(a)

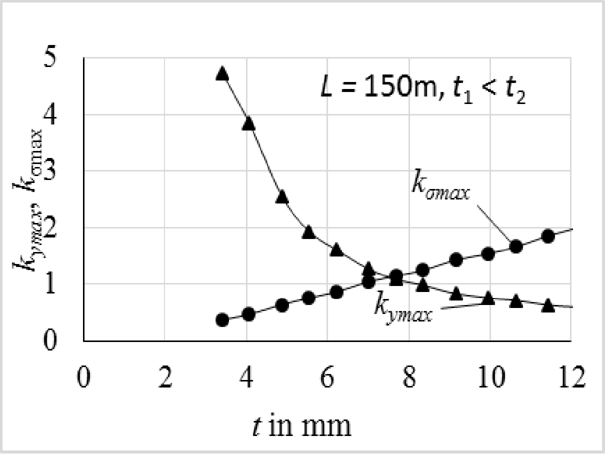
(b)

(c)

Graph 4.10. Influence of FRP Thickness t on coefficient and k_{ymax}, $k_{\sigma max}$ - where the top facesheet thickness t_1 is greater than bottom face sheet t_2 lengths between supports respectively 100, 150, 200 mm.



(a)



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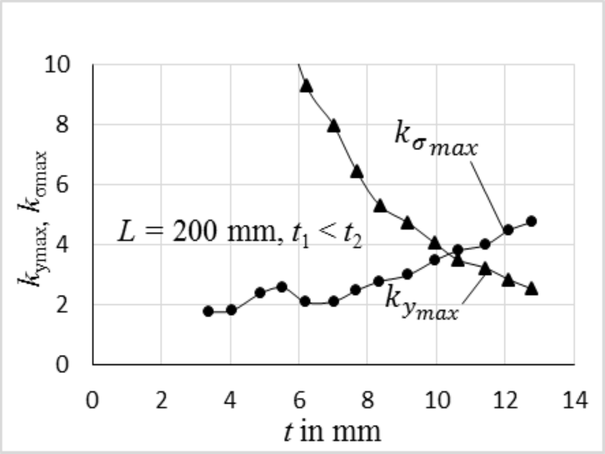
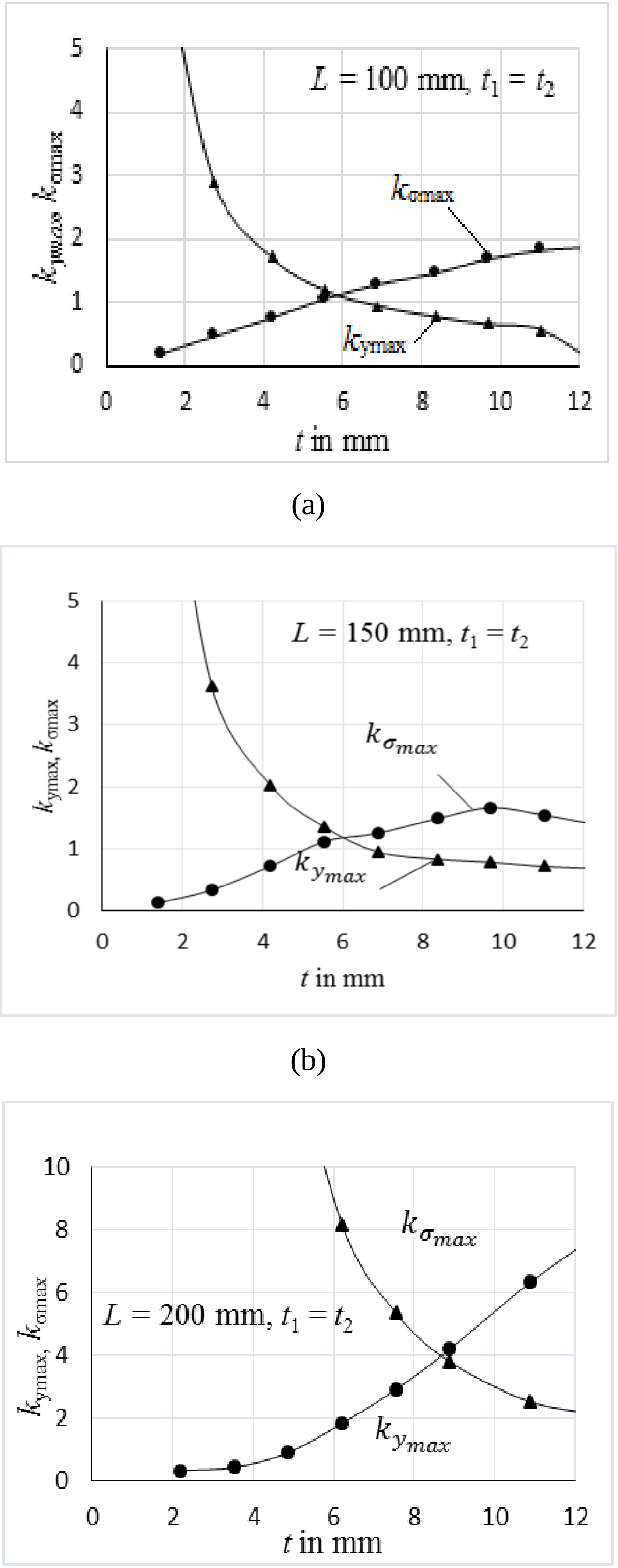


(c)

Graph 4.11. Influence of FRP Thickness t on coefficients and k_{ymax}, $k_{\sigma max}$– where the top facesheet thickness t_1 is lesser than bottom face sheet t_2 lengths between supports respectively 100, 150, 200 mm.



(a)

(b)

(c)

Graph 4.12. Influence of FRP Thickness t on coefficients and k_{ymax}, $k_{\sigma max}$ - where the top facesheet thickness t_1 is equal to bottom face sheet t_2 lengths between supports respectively 100, 150, 200 mm.

The significant effects of equivalent stress in honeycomb core were found only when the FRP thickness is low. It is clear that, when the thickness of FRP is increased and the distance between the supports decreased, the equivalent stress in the FRP have decreased. In the case of lower thickness stress on the honeycomb core FRP composite is lower than neat FRP composite in different conditions and distance between the supports. But in higher thickness value the situation is inversed and the stress on honeycomb core composite is high when compared to the neat FRP composite.

The effective performance of the honeycomb core sandwich structure can be found when the coefficients $k_{y_{\max}}$ and $k_{\sigma_{\max}}$ are higher than one.

In the above Figure 4.7, Figure 4.8, and Figure 4.9 the average range of FRP thickness for all three conditions are: when L=100 mm the thickness range is 5 -9 mm, L = 150 mm thickness range is 6 – 10 mm and L = 200 mm thickness range is 5 – 14 mm, where the condition is sustain and the range of the thickness depends on the distance between the supports. When the length between the supports increased the range of thickness is also increased.

5. ECONOMIC EVALUATION OF SANDWICH PANEL WITH OPTIMAL GEOMETRICAL THICKNESS AND MECHANICAL PROPERTIES

Based on the obtained optimal geometrical thickness of facesheet in the sandwich panel with a range of higher mechanical properties. An assumption is made for an economic forecast of the sandwich material based on the cost for existing sandwich panel (A) to the cost of sandwich panel with same facesheet and core material but optimised facesheet thickness (B). The value of the materials in the sandwich panel are mostly based on the Knowledge obtained from the expense values provided by the various sandwich panel manufacturing industrial websites and journals, because the preside calculation is impossible due to various technical and nontechnical factors usually based on manufacturing method used and quantity of the material produced, etc.

5.1. Economic Evaluation

Cost of the material used in the each component of the facesheet

Table 5.1. The cost forecast of the materials used in components of sandwich panels

Part no.	Material	Unit price, Eur/ Square Meter	Quantity, Square Meter & litters		Overall price, Eur	
			A	B	A	B
1.	Glass fibre reinforced Polyvinylester resin prepregs	3	10	7	30	21
2.	synolite 8388-P-1 resin	5	0.2	0.2	1	1
3.	Honeycomb core	10	1	1	10	10

Cost of manufacturing process

Manufacturing process of separate parts

1. Facesheet laminate:

The facesheet laminate is made by reinforcing glass fibre with polyvinylester resin as prepregs or plys. By staking the number of prepregs according to the geometrical specification, the prepregs are compressed using compression moulding machine at a specific temperature and pressure for defined period of time. These layers of prepregs are cured into a laminate which is used as facesheet. Time 20 min.

2. Honeycomb core:

Recycled paper hexagonal honeycomb impregnated in polyvinylester resin were obtained in standard size and manual cutting was done to required shape and size of the sandwich model. 10 min

3. Glue layer:

The glue was obtained readymade with required standards (synolite 8388-P-1) and it was used during the bonding of facesheet and honeycomb core.

Honeycomb core sandwich panel

1. Gluing the base of the honeycomb core and fixing it on the bottom facesheet. Time3 min
2. Gluing the top side of the honeycomb core and fixing it on the top facesheet. Time 3 min
3. The facesheets (top facesheet and bottom facesheet) were bonded with paper hexagonal honeycomb on top and bottom sides respectively and allowed to cure for a specific period of time by applying a constant pressure on it. Time 45 min

Table 5.2. Manufacturing cost and time consumption for production of honeycomb sandwich panels

Step. no	steps	Unit price in Eur	quantity	Overall price, Eur	Time, min	
					A	B
1.	Facesheet manufacturing	5	2	10	40	30
2.	Honeycomb core preparation	1	1	1	10	10
3.	Curing of sandwich panel	5	1	5	60	50
				Total due	16	110	90

Total cost of the product

The average total cost of the sandwich panel is based sum of the forecasted material cost manufacturing cost. As shown in Table

Table 5.3. Total cost forecast of honeycomb core sandwich panels

No.	cost	Overall price, Eur		Total due time, min	
		A	B		
1.	Material cost	41	32	~ 110	~ 90
2.	Production cost	16	16		
Total cost		57	48		

CONCLUSION

The aim of the thesis is to analyse the mechanical properties of the sandwich panels and find the optimal geometrical thickness of the sandwich with high strength and stiffness properties. According to the aim, the conclusions were obtained. The experimental testing of sandwich panels were performed based on the European testing standards such as for facesheets ISO 527, ISO 604, ISO14129 and honeycomb core ISO 844, ISO 1922 were used.

1. Theoretical analysis of the sandwich panels was performed using laminar theory and the results obtained were showing closer agreement with the experimental data and the graphs were plotted with mechanical properties with different angels of fiber orientation.
2. Using the experimentally obtained data of material properties a numerical FE model of the sandwich structure comprising wounded glass fibre and polyvinylester resin facesheets and recycled paper hexagonal honeycomb impregnated in polyvinylester resin was modelled using ANSYS 14.5.
3. To verify the FE model of facesheet in sandwich structure tension test was performed and the three point bending test of sandwich allowed to verify the sandwich model. The linear dependence curve showed a good agreement with the experimentally obtained curve for both tension and three point bending test.
4. On the basis of verified FE models, two other different models were generated such as a model of sandwich with honeycomb and another one without honeycomb.
5. Using these two models, a methodology was used to investigate the sandwich panel to find the optimal thickness at which the high strength and stiffness properties by varying thickness of the facesheet in three different conditions. Such as $t_1 > t_2$, $t_1 < t_2$ and $t_1 = t_2$, this methodology allowed to investigating the strength and stiffness properties at various thickness of the facesheets and distance between the supports. This helped to determine the optimal thickness value of FRP in honeycomb core composite.
6. In result of the investigation when L=100 mm the thickness range is 5 -9 mm, L = 150 mm thickness range is 6 – 10 mm and L = 200 mm thickness range is 5 – 14 mm, the optimal thickness value of FRP in honeycomb core composite was purely depends on structure geometry of material or product
7. By economical evaluation of the honeycomb sandwich composite. The average production cost of sandwich panels was estimated as 48 eur and approximate production time was estimated as 90 Min. Which is comparatively lesser than the existing material cost and production time

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APPENDIX 1

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Modelling of Honeycomb Core Sandwich Panels with Fibre Reinforced Plastic Facesheets and Analysing the Mechanical Properties

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Abstract. Using experimentally obtained specific material properties, numerical finite element models were created, one was honeycomb core sandwich structure other neat FRP composite structure was designed and experimentally verified. The honeycomb core sandwich composite comprised facesheets from wound glass fibre and polyvinylester resin and a core from recycled paper hexagonal honeycomb impregnated with polyvinylester resin and neat FRP composite structure consisted only two thin layers of facesheets. The model was used to obtain the optimal thickness of facesheet in honeycomb core sandwich structure at which the effective strength and stiffness properties can be obtained. It was determined that thickness of the facesheets had a significant effect on stiffness properties when the length between the supports are high.

Introduction

Sandwich fibre reinforced polymer (FRP) composites have emerged as important material because of their high specific strength and high specific stiffness, light weight, high fatigue resistance compared to common metallic alloys. Composite materials are used in almost all aspects of industrial and commercial fields such as ships, aircrafts, and general vehicles [1-2]. Honeycomb structures are especially becoming more prevalent in the field of civil engineering where the need of high structural strength and low weight is necessary [3].

Sandwich panels consist of two thin facesheets covering the light weight core. For numerical analysis of honeycomb sandwich structure various modelling approaches are developed. The finite element analyse is one of the means used to find the approximation of global behaviour of the sandwich panels [4-5]. The high mechanical performance with minimum unit weight can be provided by fibre reinforced polymer honeycomb sandwich structure [6].

In order to increase the performance and use of honeycomb sandwich material in different applications, knowledge of the mechanical behaviour is required. This motivates to develop complex numerical models and experimental methods, which characterise the design, material models and optimizing the honeycomb sandwich panels in certain specific conditions.

The object of the investigation is the sandwich composite with facesheets made of wounded glass fibre and polyvinylester resin and core made of recycled paper hexagonal honeycomb impregnated in polyvinylester resin.

The aims of this study are to find the appropriate numerical material models and compare these models with experimental data; using obtained numerical models to determine the optimal thickness of facesheet in honeycomb sandwich structure at which the effective optimal strength and stiffness properties are obtained and increase the mechanical behaviour of sandwich structure.

Material and Modelling

The sandwich structure presented in Figure 1 was used for the investigation. In order to find the mechanical properties of the sandwich materials various tests were carried out according to the standards. For facesheets ISO 527, ISO 604, ISO14129 and honeycomb core ISO 844, ISO 1922 were used. The obtained mechanical properties are presented in Table 1 and Table 2. According to the obtained material properties of the honeycomb it is found that material is highly anisotropic. The average thickness of the ply was 0.7 mm and fibre volume was 43%.

Figure 1. Model of sandwich with honeycomb core.1 – woven glass fibre and polyvinylester resin composite facesheet; 2 - recycled paper hexagonal honeycomb impregnated in polyvinylester resin.

Table 1. Mechanical properties of FRP facesheet.

Mechanical properties	**Value**	**Units**
Tension strength	645	MPa
Compression strength	248	MPa
Longitudinal young's modules E_1	37.5	GPa
Transverse young's modules E_2	7.32	GPa
Poisson's ratio ν_{12}	0.28	-
Poisson's ratio ν_{21}	0.05	-
Shear modules G_{12}	3.79	GPa
In plain shear strength, S_{12}	23.0	MPa

Table 2. Mechanical properties of paper honeycomb core.

Mechanical properties	**Value**	**Units**
Young's modules	10	MPa
Compression strength	0.48	MPa
Shear modules	235	MPa
Shear strength	0.64	MPa

The recycled paper hexagonal honeycomb impregnated with polyvinylester resin was used for sandwich core thickness of wall was 0.22 mm, height was 10 mm, and edges was 10mm. the model was modelled using shell element for facesheet and solid element for honeycomb core.

According to experimentally obtained data the models of honeycomb core sandwich structure (with a honeycomb) and neat FRP facesheet material (without the honeycomb) were created using finite element modelling in ANSYS 14.5 as shown in Figure 2. The bonding between the honeycomb core and the facesheet was modelled with a "glue" layer with the thickness of 0.05 mm. The properties of the glue for the numerical model were defined as the mechanical properties of synolite 8388-P-1 resin (Young's modulus and tensile strength were 3.7 GPa and 14 MPa, respectively).

Verification of facesheet material model was performed using linear analysis by simulating tension test. Previously, an experimental test was carried out. The laminate code was [±65/90], the thickness of the plies were 0.9 mm and 0.75 mm for ±65 and 90 plies, respectively. The total thickness was 2.4 mm. Stress versus strain was measured in this test and the linear dependence curve shows a good agreement with experimentally obtained curve as shown in Figure 3.

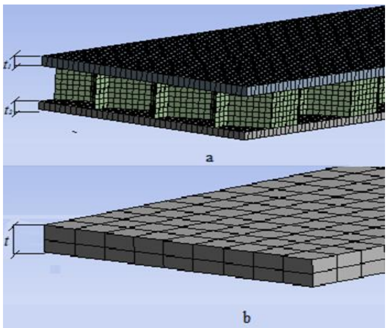


Figure 2. Models: (a) - model of honeycomb core sandwich composite; (b) – model of neat FRP sandwich composite. t_1 & t_2 - thickness of top facesheet and bottom facesheet; t ($t = t_1+t_2$) – thickness of neat FRP sandwich

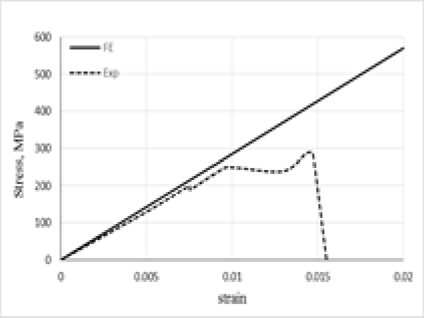


Figure 3. Tension stress – strain curve of FRP composite

Verification of the sandwich structure model was performed using linear analysis by simulating three point bending test. Previously, an experimental test was carried out. The dimensions of the specimens were as follows: width 60 mm, distance between the supports 200 mm, thickness of the top facesheet 2.68 mm, the thickness of bottom facesheet 2.81 mm, the core thickness 10 mm and thickness of sandwich 15.5 mm. The force versus deflection was measured during this test and the linear dependence curve of FE model shows a good agreement with experimental obtained curve as shown in Figure 4.

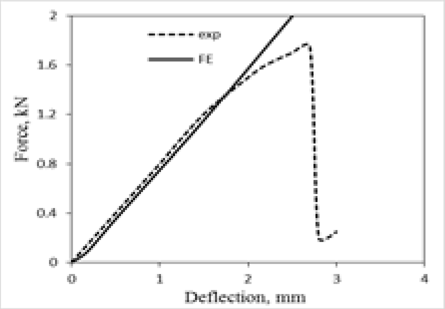


Figure 4. Force versus deflection curve obtained experimentally and by FE simulation

Using verified model the quasi-static in three point bending tests were simulated. A constant load of 800 N was applied in all simulation. This investigation was carried out in three different ways by varying the facesheet thickness. Such as $t_1 > t_2$, $t_1 < t_2$, $t_1 = t_2$ (t_1- thickness of top facesheet and t_2- thickness of bottom facesheet). In first condition $t_1 > t_2$ where, thickness of the top face sheet t_1 is varied by increasing the plys for each simulation and the bottom facesheet thickness t_2 was kept constant. In second condition $t_1 < t_2$ where thickness of the bottom facesheet t_2 was varied by increasing the plys for each simulation and top facesheet thickness t_1 was kept constant. In third condition were $t_1 = t_2$ thickness of the both facesheets t_1 and t_2 were changed equally by adding the equal number of layers for each simulation. Laminate code for the top facesheet and the bottom facesheet were changed as $[\pm 65]_n$ and $[\pm 65/90]_n$ respectively.

The thickness of facesheet was increased step by step in every investigation and three point bending simulation was simulated as shown in Figure 5. For each thickness change of facesheet, deflection and maximum equivalent stress the maximum equivalent stress was measured on middle of sandwich panel (Point where the load was applied in sandwich structure).

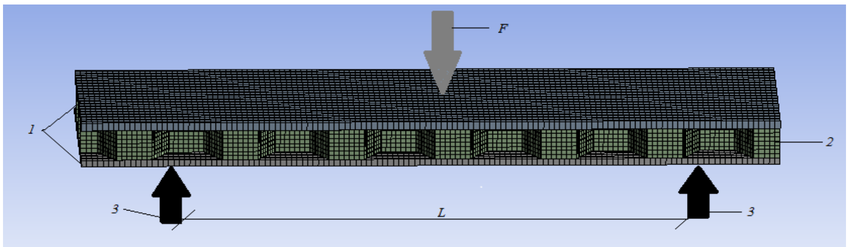


Figure 5. The numerical model of three point bending specimen. F - force applied, 1 - facesheets, 2 - hexagonal honeycomb core, 3 - supports, *L* – length between the supports.

For both honeycomb core sandwich structure and neat FRP composite the stiffness were calculated according to the equation:

$$K = \frac{F}{y_{\max}} \tag{1}$$

Where *K* – stiffness, *F* – force applied, y_{max} – maximum deflection.

The maximum deflection coefficient $k_{y_{\max}}$ which can be represented as ratio of maximum deflection of neat FRP composite to the maximum deflection of honeycomb core composite structure was used:

$$k_{y_{\max}} = \frac{y_{\max_1}}{y_{\max_2}} \tag{2}$$

Where $y_{\max_1}$ - maximum deflection of neat FRP composite; $y_{\max 2}$ - maximum deflection of honeycomb core composite structure.

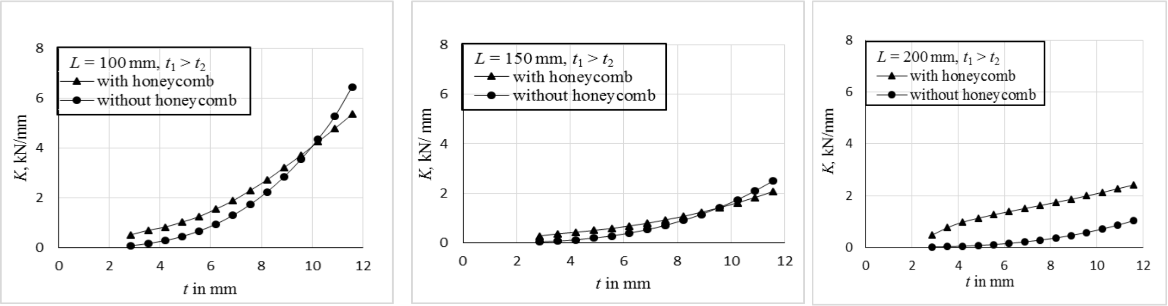
The coefficient $k_{\sigma_{\max}}$ represented the ratio of maximum stress σ_{max} of neat FRP composite to the maximum stress of honeycomb core FRP sandwich. This can be expressed as:

$$k_{\sigma_{\max}} = \frac{\sigma_{\max_1}}{\sigma_{\max_2}} \tag{3}$$

Where $\sigma_{\max_1}$ – maximum equivalent stress of neat FRP composite; $\sigma_{\max 2}$ – maximum equivalent stress of honeycomb core composite structure.

Result and discussion

The stiffness variation influenced by thickness of FRP was calculated for both honeycomb core sandwich structure and neat FRP. The stiffness increases as the thickness of the FRP increases in all the cases. For lower thickness value, stiffness for honeycomb sandwich structure is higher than neat FRP composite. At a particular thickness value, stiffness of both honeycomb sandwich structure and neat FRP are same, but that particular point differs depending on the thickness orientation and distance between the supports. For $t_1 > t_2$ when $L = 100$ mm the value is $t = 9 – 10$ mm, when $L = 150$ mm the value is $t = 10 – 11$ mm, when $L = 200$ mm twice higher the other thickness. For $t_1 < t_2$ when $L = 100$ mm the value is $t = 7 – 8$ mm, when $L = 150$ mm the value is $t = 8 – 9$ mm, when $L = 200$ mm the value is twice higher the other thickness. For $t_1 = t_2$ when L=100 mm the value is $t = 8 – 9$ mm, when $L = 150$ mm the value is $t = 9 – 10$ mm, when $L = 200$ mm the value is also double. Below this thickness value, stiffness of the honeycomb core sandwich structure is higher than the neat FRP. In the same case above this thickness value, stiffness of the neat FRP is higher than the honeycomb core sandwich structure. The graph clearly represents that stiffness value of $L = 100$ mm higher than $L = 150$ mm that is more or less double the value also in $L = 200$mm.



a b c

Figure 6. Influence of FRP thickness t on stiffness K: a, b, and c – where the top facesheet thickness t_1 is greater than bottom face sheet t_2 lengths between supports respectively 100, 150, 200 mm.

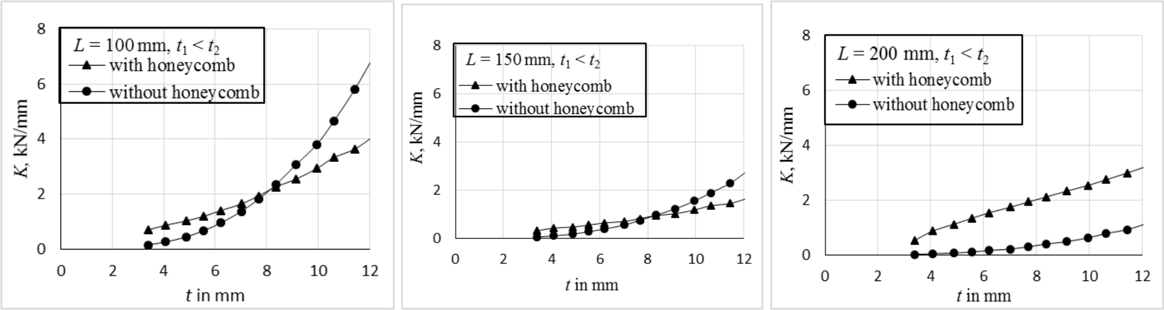


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Figure 7. Influence of FRP Thickness t on stiffness K: a, b, and c – where the top facesheet thickness t_1 is lesser than bottom face sheet t_2 lengths between supports respectively 100, 150, 200 mm.

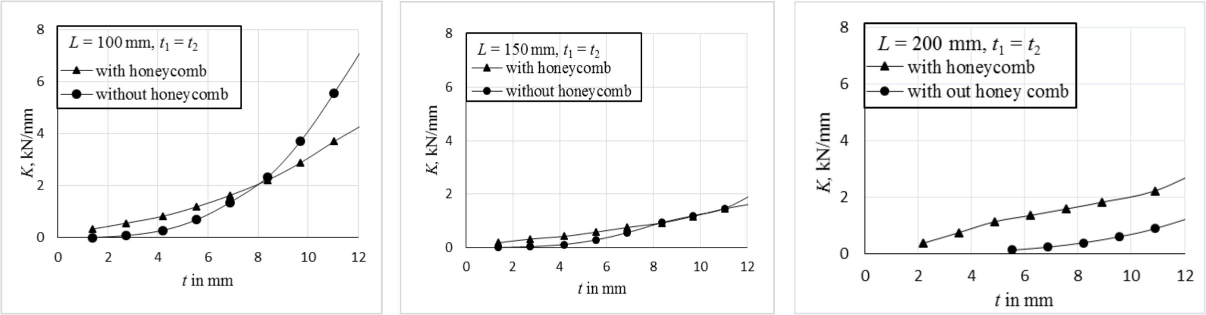

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Figure 8. Influence of FRP Thickness t on stiffness K: a, b, and c – where the top facesheet thickness t_1 is equal to bottom face sheet t_2 lengths between supports respectively 100, 150, 200 mm.

By only comparing the optimal thickness, stiffness of the composite is not so clear because of the same value of stiffness can be obtained from constant F and different y_{max} values. So influence of thickness separately on y_{max} and $\sigma_{\max}$ were investigated.

The coefficient $k_{y_{\max}}$ and $k_{\sigma_{\max}}$ are defined by y_{max} and σ_{max} values, which is obtained from different thickness and length between the supports. It is clear that the deflection decreases when the thickness of the FRP increases and the distance between the support decreases. The effects of the maximum deflection value of honeycomb core composite was found only when the thickness of FRP is lower and distance between the supports is increased.

In case of neat FRP composite, it has the minutiae stiffness in the lower thickness values so coefficient $k_{y_{\max}}$ cannot be calculated

In contrast for thickness *t* equal to 5 mm (at this value honeycomb height is 80% of the total composite thickness [7, 8]). The deflection of the honeycomb core FRP composite is close to 2.1, 2.6, and 14 times lower than the neat FRP composite in all three conditions as the distance between composite are 100, 150 and 200.

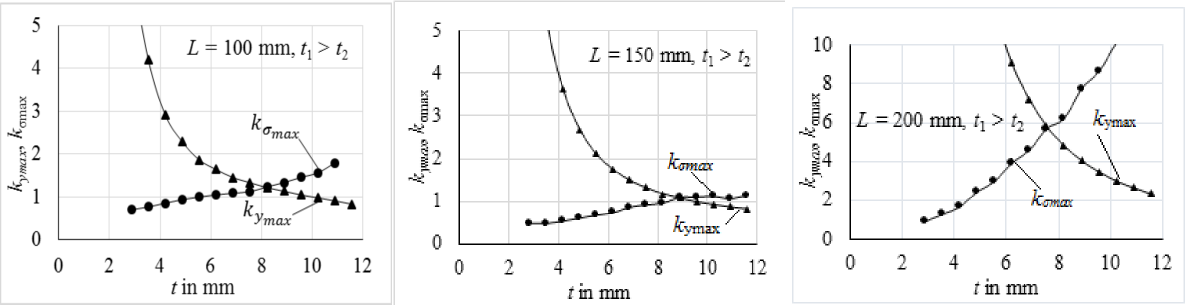

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Figure 9. Influence of FRP Thickness *t* on coefficient $k_{y_{\max}}$ and $k_{\sigma_{\max}}$ - where the top facesheet thickness t_1 is greater than bottom face sheet t_2 lengths between supports respectively 100, 150, 200 mm.

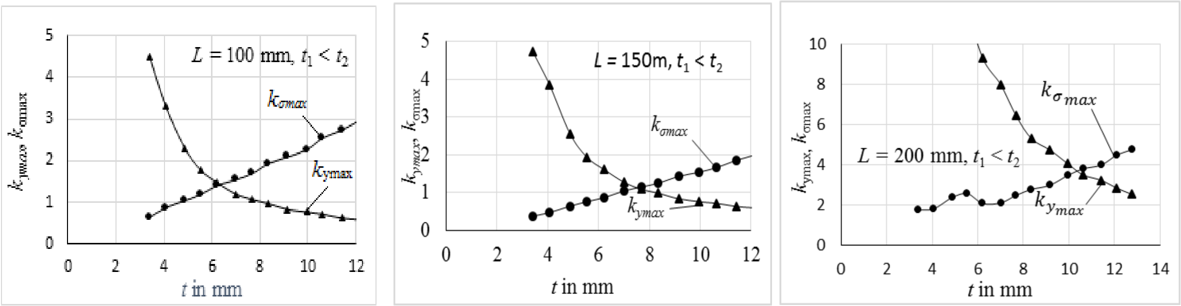

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Figure 10. Influence of FRP Thickness *t* on coefficient $k_{y_{\max}}$ and $k_{\sigma_{\max}}$ – where the top facesheet thickness t_1 is lesser than bottom face sheet t_2 lengths between supports respectively 100, 150, 200 mm.

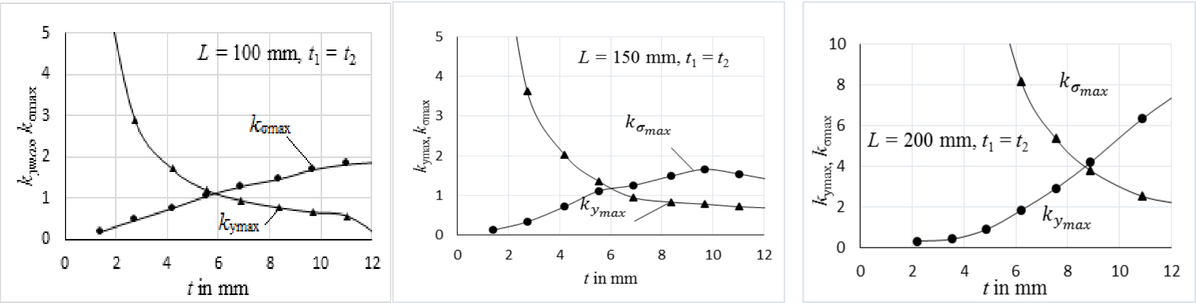

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Figure 11. Influence of FRP Thickness *t* on coefficient $k_{y_{\max}}$ and $k_{\sigma_{\max}}$ - where the top facesheet thickness t_1 is equal to bottom face sheet t_2 lengths between supports respectively 100, 150, 200 mm.

The significant effects of equivalent stress in honeycomb core were found only when the FRP thickness is low. It is clear that, when the thickness of FRP is increased and distance between the supports decreased, the equivalent stress in the FRP have decreased. In case of lower thickness stress on the honeycomb core FRP composite is lower than neat FRP composite in different conditions and distance between the supports. But in higher thickness value the situation is inversed and the stress on honeycomb core composite is high when compared to the neat FRP composite.

The effective performance of the honey combe core sandwich structure can be found when the coefficients $k_{y_{\max}}$ and $k_{\sigma_{\max}}$ are higher than one.

In the above Figure 9, Figure 10, and Figure 11 the average range of FRP thickness for all three conditions are: when L=100 mm the thickness range is 5 -9 mm, L = 150 mm thickness range is 6 – 10 mm and L = 200 mm thickness range is 5 – 14 mm, where the condition is sustain and the range of the thickness depends on the distance between the supports. When the length between the supports increased the range of thickness is also increased.

Conclusions

An analysis of strength and stiffness of sandwich structure comprises of honeycomb core sandwich and neat FRP were carried out.

The material of the separate components of sandwich structures were tested and the mechanical properties were obtained. Using the material properties a numerical model of sandwich structure comprising wounded glass fibre and polyvinylester resin facesheets and recycled paper hexagonal honeycomb impregnated in polyvinylester resin was modelled. The Facesheet tension test and three point bending of sandwich structure allowed to verify the FE model of facesheet material and sandwich structure.

The methodology used for investigation of the sandwich structure by changing the thickness of the facesheets in three different conditions such as $t_1 > t_2$, $t_1 < t_2$ and $t_1 = t_2$, this methodology allowed to investigating the strength and stiffness properties at various thickness of the facesheets and distance between the supports. This helped to determine the optimal thickness value of FRP in honeycomb core composite.

In result of the investigation, the optimal thickness value of FRP in honeycomb core composite was purely depends on structure geometry of material or product.

It is also equally important to consider the distance between the supports which influence the thickness variation of the FRP facesheets in honeycomb core sandwich composite.

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APPENDIX 2

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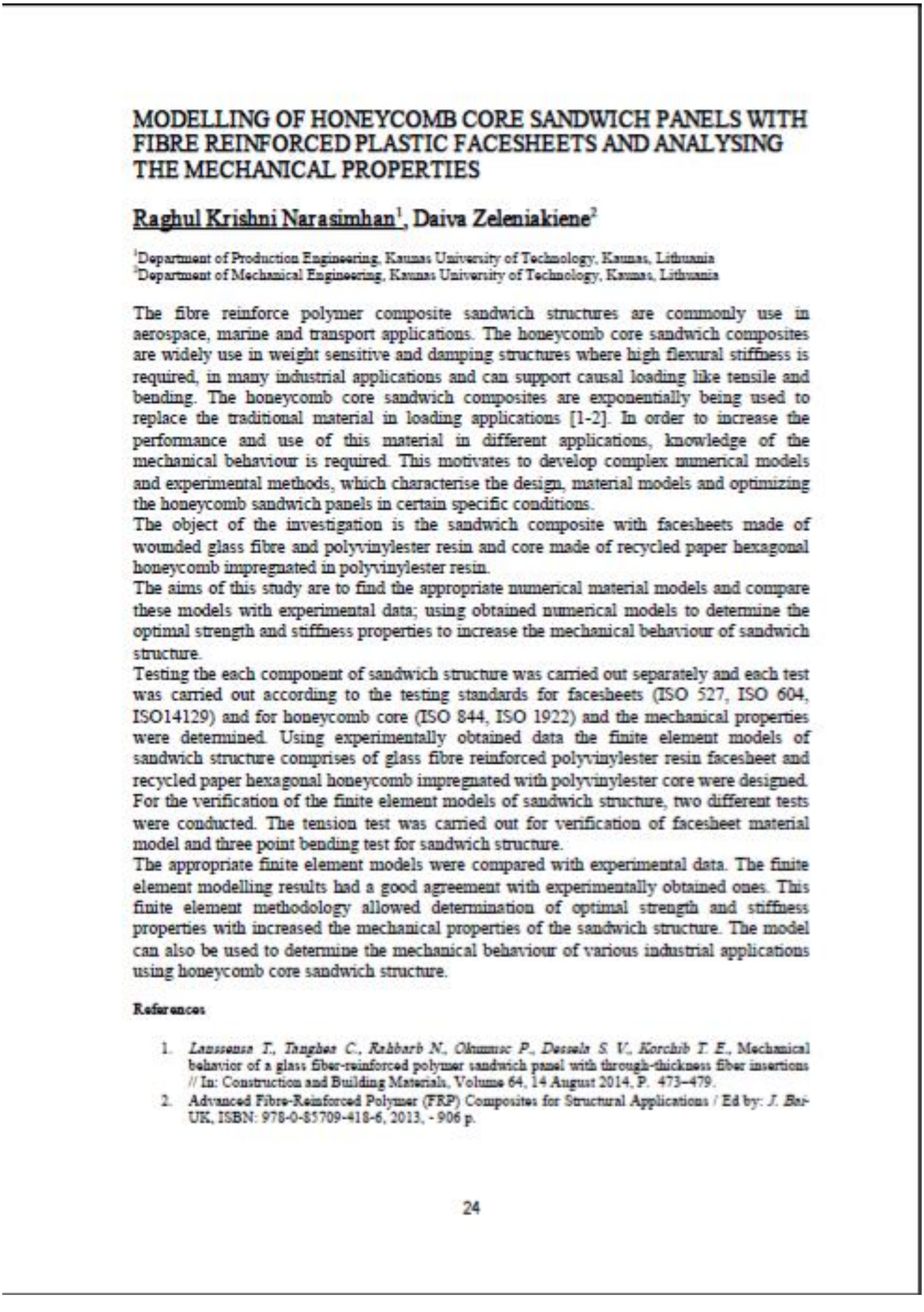

MODELLING OF HONEYCOMB CORE SANDWICH PANELS WITH FIBRE REINFORCED PLASTIC FACESHEETS AND ANALYSING THE MECHANICAL PROPERTIES

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The fibre reinforce polymer composite sandwich structures are commonly use in aerospace, marine and transport applications. The honeycomb core sandwich composites are widely use in weight sensitive and damping structures where high flexural stiffness is required, in many industrial applications and can support causal loading like tensile and bending. The honeycomb core sandwich composites are exponentially being used to replace the traditional material in loading applications [1-2]. In order to increase the performance and use of this material in different applications, knowledge of the mechanical behaviour is required. This motivates to develop complex numerical models and experimental methods, which characterise the design, material models and optimizing the honeycomb sandwich panels in certain specific conditions.

The object of the investigation is the sandwich composite with facesheets made of woumded glass fibre and polyvinylester resin and core made of recycled paper hexagonal honeycomb impregnated in polyvinylester resin.

The aims of this study are to find the appropriate numerical material models and compare these models with experimental data; using obtained numerical models to determine the optimal strength and stiffness properties to increase the mechanical behaviour of sandwich structure.

Testing the each component of sandwich structure was carried out separately and each test was carried out according to the testing standards for facesheets (ISO 527, ISO 604, ISO14129) and for honeycomb core (ISO 844, ISO 1922) and the mechanical properties were determined. Using experimentally obtained data the finite element models of sandwich structure comprises of glass fibre reinforced polyvinylester resin facesheet and recycled paper hexagonal honeycomb impregnated with polyvinylester core were designed. For the verification of the finite element models of sandwich structure, two different tests were conducted. The tension test was carried out for verification of facesheet material model and three point bending test for sandwich structure.

The appropriate finite element models were compared with experimental data. The finite element modelling results had a good agreement with experimentally obtained ones. This finite element methodology allowed determination of optimal strength and stiffness properties with increased the mechanical properties of the sandwich structure. The model can also be used to determine the mechanical behaviour of various industrial applications using honeycomb core sandwich structure.

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