TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY

ANTTI SAARINEN

SHEAR STRENGTH EXAMINATION OF THE MINERAL WOOL LAMELLA CORED SANDWICH PANELS AND THE COMPARISON OF THEIR DIFFERENT END CONNECTIONS

Master of Science thesis

Examiner: prof. Markku Heinisuo
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ABSTRACT

ANTTI SAARINEN: The shear strength examination of the mineral wool lamella cored of sandwich panels and the comparison of their different end connections
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The sandwich panels with the mineral wool core contain mineral wool lamellas. The end connections of lamellas have not been studied much and it is unclear how different end connection types affect to the total strength of the whole panel. European product standard EN 14509:2013 describes two different test methods for shear strength. With them, it is possible to examine the shear strength of sandwich panels and mineral wool lamellas. However, these test methods do not work well when the thickness of panel is over 100 mm.

In the first part of this thesis, the functional test method was developed to test the shear strength of the thicker lamellas. The previous tests and EN 14509:2013 part A.3 were the basis for the development. The developed test method is usable with glass wool and also with the stronger stone wool.

After the test method development, different end connections were studied in the second part of the thesis. Their strength was compared with the strength of full lamella. Both, mechanical end connections and glue end connections were examined. The mechanical end connection types meant the shaped connections which were made by milling and cutting. Other possible mechanical end connections are also included.

All the test specimens were handmade. The results of tests show that the glue end connections are stronger than the mechanical end connections. The stiffness of the glue end connections was higher. The amount of glue and spreading pattern had effect on the strength of the connection and further inspections about this are recommended to be done.

TIIVISTELMÄ

ANTTI SAARINEN: Mineraalivillalamellisten sandwich-paneelien leikkauslujuustarkastelu ja lamellien erilaisten liitosvaihtoehtojen vertailu
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Villaytimiset sandwich-paneelit koostuvat mineraalivillalamelleista. Lamellien liitosten ja eri liitostyyppien vaikutuksesta rakenteen kestävyyteen ei ole olemassa juurikaan tutkimusta. Eurooppalainen tuotestandardi EN 14509:2013 kuvaa leikkauslujuuden testaamiseen kaksi erilaista testimenetelmää, joiden avulla paneelin ja lamellien leikkauslujuutta voidaan tarkastella. Nämä testit eivät kuitenkaan toimi oikein kun lamellien paksuus ylittää 100 mm.

Tämän diplomityön ensimmäisessä osassa kehitettiin toimiva testimenetelmä paksumpien lamellien leikkauslujuuden määrittämiseen. Pohjana tälle toimi aikaisemmat testikokeilut sekä EN 14509:2013 kohta A.3. Koejärjestelystä kehitettiin sellainen, että se toimii niin lasivillan kuin sitä lujemman kivivillan kanssa.

Testimenetelmän kehittämisen jälkeen, diplomityön toisessa osassa, tutkittiin erilaisten liitostyyppien kestävyyttä suhteessa kokonaiseen lamelliin. Sekä mekaanisesti toteutettuja että liimauksen avulla toteutettuja liitostyyppejä tutkittiin. Mekaaniset liitokset tarkoittivat jyrsimällä ja leikkaamalla toteutettuja muotoiltuja lamellin päitä sekä muita mahdollisia mekaanisia liitoksia.

Käsin tehtyjen koekappaleiden tuloksien pohjalta voitiin todeta että liimaamalla toteutetut lamelliliitokset ovat kestävämpiä kuin mekaaniset liitokset. Liimattujen liitosten jäykkyys oli myös parempi. Tosin liitoksen liimamäärä ja liiman peittokuvio vaikuttaa oleellisesti liitoksen kestävyyteen ja tämän suhteen on suositeltavaa tehdä vielä jatkotutkimuksia.

PREFACE

This Master Thesis has been made at Technical University of Tampere to the Department of Civil Engineering. The topic of the thesis was provided by Ruukki Construction Oy and it was also the investor of the thesis.

The examiner of this thesis has been Professor Markku Heinisuo I want to thank him for patience support during the writing process. I want to express my gratitude to Simo Heikkilä and Lars Heselius. Without their help and advice, this research would have been much more abridged. I want also thank the staff of Alajärvi factory. They helped me much during the test phase.

I am grateful to my family and friends who have supported me during the process. Their advice has opened new perspective to the thesis and your company has carried me over the most stressing parts. Special thanks to Johanna, who was the proofreader of this thesis.

Tampere, 12.12.2015

Antti Saarinen

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1. INTRODUCTION

1.1 General

This thesis is made for Ruukki Construction at their factory at Alajärvi. Thesis is focused only on wool lamellas of sandwich panels that are manufactured in Alajärvi. The work on the thesis was started on June 2015

The topic was provided by Ruukki Construction and thesis is part of mineral wool core sandwich panel development. Only sandwich panels with mineral wool core and flat or lightly profiled steel faces are examined in this research. Other panel types are mentioned shortly and used as examples of when needed.

Some minor researching and testing was made around the end of the year 2014 and spring of 2015. During this time, useful data was collected, but no specific work and test method was used or designed. This thesis exploits the previously collected data about the test method and examines test method versions used earlier.

1.2 Aim of the thesis

The core of sandwich panel consists of mineral wool lamellas. The aim of this thesis is to find a method how to test those lamellas under shear forces. In this thesis, two terms are used. A beam means a mineral wool core piece which has metal face sheets on the exterior and interior surfaces. A mineral wool lamella instead means just the core of the beam. Mineral wool includes used wool types, glass wool and stone wool.

At the moment, there are two test methods which can be used in shear testing. EN 14509:2013 A.3 is used for beam testing. However, it does not work well with beams which are thicker than 100 millimeter. EN 14509:2013 A.4 test method is used to test full-scale sandwich panels. This test method requires space and full-scale panels and because of that, it is not convenient to study one lamella.

The first part of testing is finding the right method of measuring the shear strength in continuous lamellas. The continuous lamella is lamella made from one mineral wool piece and it does not have any end connections in it. The end connection means a connection between two lamellas.

One lamella was chosen to be the test subject, because it resembled close enough a full-scale sandwich panel. It was also assumed that effect of end connection is stronger in the lamella alone. In the full-scale panels, adjacent, continuous lamellas support the lamella with end connection. The end connections of mineral wool lamellas are usually located in the sandwich panel like is shown on **Error! Reference source not found.**, but positioning of end connections can be also something different because it is a manufacturer and panel type dependent characteristic. Other reason was lack of time as full-scale tests are time-consuming.

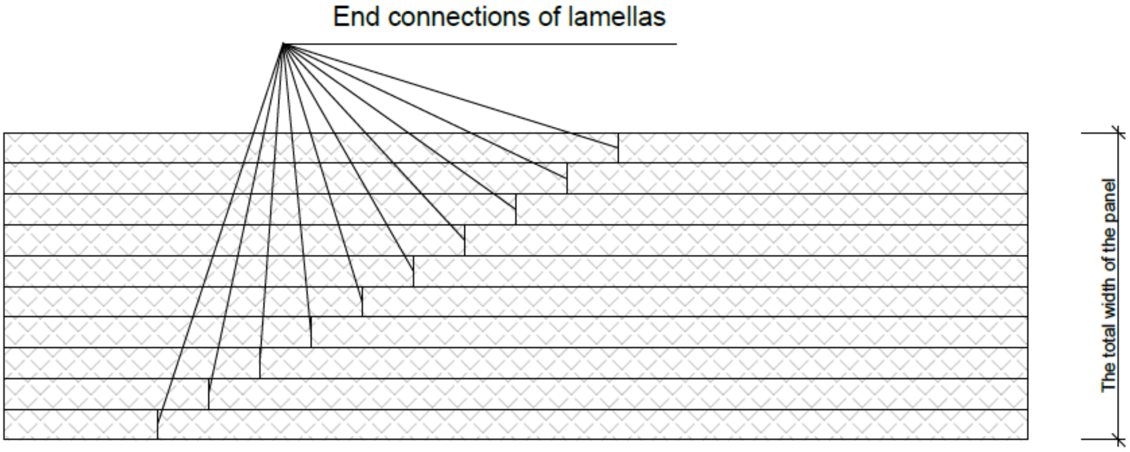


Figure 1: *the lamellas layout in a sandwich panel*

By finding the right test method for complete lamella, it is possible to test and improve technical properties of mineral wool lamella connections inside a sandwich panel. During the research different connection types were studied and hopefully one will be chosen for the further inspection and will be used in the manufacturing process.

At the moment, panels are made according to SFS-EN 14509, and it does not define any end connection type which should be used. Sandwich panels with lamella end connections of that kind are not strong enough under shear and their flexural rigidity or compressive strength is not high in comparison with similar panels with a thinner insulation layer. The main problem with straight edges is that lamellas can slide in the connection under shear stress; this is shown on Figure 2.

Figure 2: *Sliding in the end connection during long term loading test*

Sliding usually happens under long term loading. Short term loadings are not usually large enough to affect and maintain this phenomenon. Sometimes unexpected short term loads appear and a sandwich panel starts to fail from the end connection of lamellas. During this research, the goal is to find the proper test method which leads to shear failure in a lamella. This is the only way to study different end connection types.

Mineral wool lamellas do not work together as a core similarly than polyurethane core acts on panels and that is the reason why theories and test methods from PUR or PIR panels cannot be used directly on mineral wool cores. The area near lamella connections is a little bit weaker than the center of the lamella in mineral wool panels.

In this research, different joint possibilities are studied and compared. Possible techniques are joints made with glue or some kind of peg or a mechanical connection, where ends of lamellas are modified and formed.

With proper lamella end connections, sandwich panels have higher strength against loads with a thicker core and that is the reason why this research is done. Longer spans can be achieved with panels having higher mechanical performance and this reduces construction costs, because fewer columns and beams are needed.

After finding the usable test method, different connections options are tested and compared with each other. All connection types have different impacts on manufacturing and thus they are also examined. Fire safety plays a role in choosing the connection type as fire regulations limit the amount of inflammable materials in the final product.

1.3 Methods and timetable

The thesis contains three parts. The first part contains some regulations given by the Euronorms and presents the theory of sandwich panels and mineral wool lamellas. The second part describes test methods and the third part reveals the test results.

Theory was based on books, articles and researches about sandwich structures and sandwich panels. Sandwich structures are widely used in different applications and places and the same principles apply for all sandwich structures. Mineral wool cores are only used in structural sandwich panels and after the general theory, the thesis was concentrated mainly on sandwich panels used in construction.

Sandwich panels are specified by European standard EN 14509-2013. This limits acceptable solutions to a few and nowadays sandwich panels are widely standardized. Manufacturing conditions and wanted quality both are the reasons why totally different panels cannot be considered reliable.

Harmonized product standard EN 14509-2013 determinates standard test methods for sandwich panels. Those tests are required to archive CE marking. They are just guidelines and manufactures can modify them under specific circumstances. In this thesis, those circumstances are described and some used test methods are shown. The problem is that EN does not contain a totally applicable and suitable test method for the lamella-cored of a sandwich panel.

The whole panel bending resistance, shear resistance and durability under tension and compression can be tested by the following EN. However shear inside the specific area of sandwich panel is challenging to measure. The basis for the shear strength test is a beam test which is used in tests for pure mineral or glass wool.

Second part also contains research about the proper method of testing to test the strength of a joint of mineral wool lamella. EN 14509-2013 does not give any special test method for mineral wool lamellas and one goal of the thesis was to create the functional method for that.

The basis was EN 14509:2013 test method A.3. The mineral wool properties vary so much that the dimensions of the test specimen which work during the shear test, were very challenging to calculate. The shear and compression strength of lamella are so close to each other that during the test, failure can happen by compression or shear. This is a problem especially with stronger mineral wools.

The search for the right test method started with pilot test series whose goal was to find the right dimensions for the test specimen and test apparatus so shear failure was ensured. 0-serie was made after the pilot series to acquire comparative results for joint testing. The pilot and 0-series were made with full lamellas.

The shear strength tests of this thesis were made mainly with lamellas. Full scale panel tests are possible but very challenging to make. The main reason is that full-scale test specimens must be done by hand and the costs of doing full-scale testing is much higher than beam tests.

However, during the reference series, it was discovered that test apparatus works with test specimens who contain three lamellas. This kind of miniature sandwich panel test was made with few different end connection types and the results were collected. Hopefully this thesis gives enough information about how to design and perform full scale tests and which kind of end connection should be chosen to be tested

The search for the test method began in June 2014 and continued slowly during the fall and winter. This research process started officially in August 2015 with start meetings at Alajärvi and Hämeenlinna.

During the research, meetings were held when necessary. The test method was planned and developed by Antti Saarinen, Simo Heikkilä, Harri Kemppainen and Lars Heselius. The purpouse of meetings was to come to an agreement on the structure of the test method and to view the matter from various perspectives. The participation of several parties helped to take into account how various end connection types fit in with testing, manufacturing and safety requirements.

In these meetings, next things were chosen to be done during fall 2015:

1. Introduction to the test method,
2. Pilot testing with whole lamellas and the test method development,
3. The test method evaluation,
4. Reference tests with the whole lamella and shear strength calculation,
5. The actual end connection tests and shear strength of the connection,
6. Comparison of end connection types.

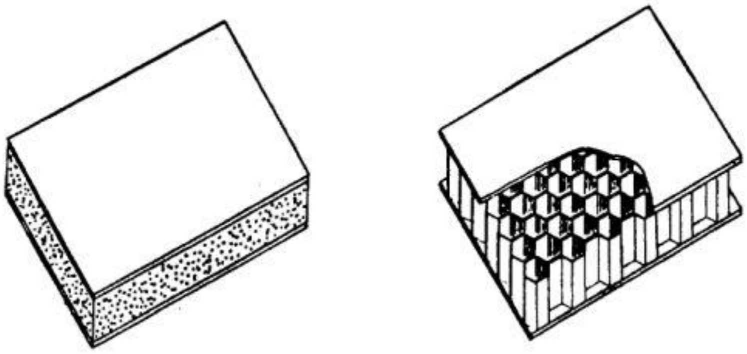
The original time plan for testing is in the appendix A. The goal was to have test results of end connections before December 2015 and know what impact each end connection type has to manufacturing.

2. SANDWICH STRUCTURE

2.1 Sandwich structure generally

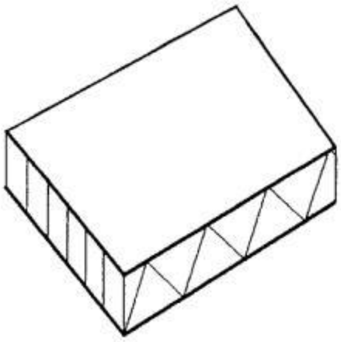
Sandwich panels have become widely used structural solution for many different places after they were invented the 1960s. Light weight and strength are common features for all sandwich structures. Sandwich panels are also energy efficient and they make construction work easy. The first sandwich structures were almost only confined to spaceships and space technology, but soon other alternative uses were discovered. (Davies et al. 2001)

The structure of sandwich panels is always the same. The structure contains at least two surface layers and core layer. Surfaces layers are thin and stiff compared to the core material, which is thick and light. Together these layers form adequate stiffness and yet the structure is still light. Choosing different materials for layers gives a great amount of alternative forms of sandwich structures. (Carlsson, Kardomateas 2011) Figure 3 shows some typical sandwich structures.



(a) Expanded plastic core

(b) Honeycomb core



(c) Mineral wool core

Figure 3: *Examples of sandwich structures (Davie et al.s 2001)*

Face sheets and core combination are like an I-beam structure but in two dimensions. Surface layers works as a support structure for bending loads and the purpose of the core is to transfer shear force between the faces in a sandwich panel under load. The combination works efficiently as a load-carrying structure.

Thin surface layers are usually made from comparably dense material which is stiff and strong. Different metals, plastic or fiber composite can be used as surface materials, for example.

Core constructions can be separated into two categories: “cellular” and “structural”. The cellular core is comprised of cellular foam which is enclosed by surface layers. Foam fills the space between faces constantly so the structure works as one piece. Polymers, metal foams, honeycomb core or balsa wood are examples of cellular cores. Structural cores usually contain some solid material formed to connect external and internal faces. Those kinds of cores are also called web core and they are illustrated on Figure 4. Core material forms a continuous web which works as shear force transfer. (Carlsson, Kardomateas 2011)

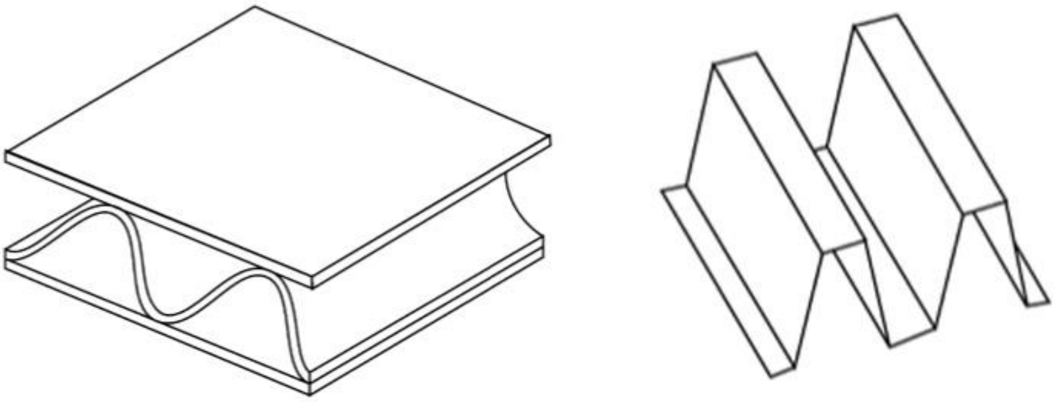


Figure 4: *Web cores (Calsson & Kardomateas 2011)*

2.2 Sandwich panels used in construction

Sandwich panels in constructions follow the same principles as any other sandwich structures. Surfaces are commonly thin compared with a core and vary between 0.5 and 0.7 millimeters, but in some cases thickness can be even 2.0 millimeters. Core material works often also as insulation and thickness starts from 30 mm and increases all the way to 300 mm. (European Recommendations for Sandwich Panels, 2000)

Metal is the most commonly used face sheet material in sandwich panels used in building construction. Face sheets can be made of aluminum, steel, stainless steel or copper.

Types of sandwich panels' faces can be divided into three categories. Surface layer can be totally flat, lightly profiled or profiled. Flat faces are more difficult to manufacture compared with other face profiles. Flat surfaces are vulnerable to dents and at the edges of panels folding the faces are necessary for joints.

Sandwich panels are considered as lightly profiled when rib depth is less than 2 millimeters. Profiling has a great impact on the technical properties of the sandwich panel. The most significant increase is in a wrinkling stress. Profiling gives a different aesthetic appearance to choose. Sandwich panels with profiling higher than 2 mm are called profiled face panels. All three types of faces are shown on Figure 5. (Mahendran & Pokharel 2004) EN 14509:2013 determinates 5 mm to the limit and panels with higher profiles are called profiled face panels.

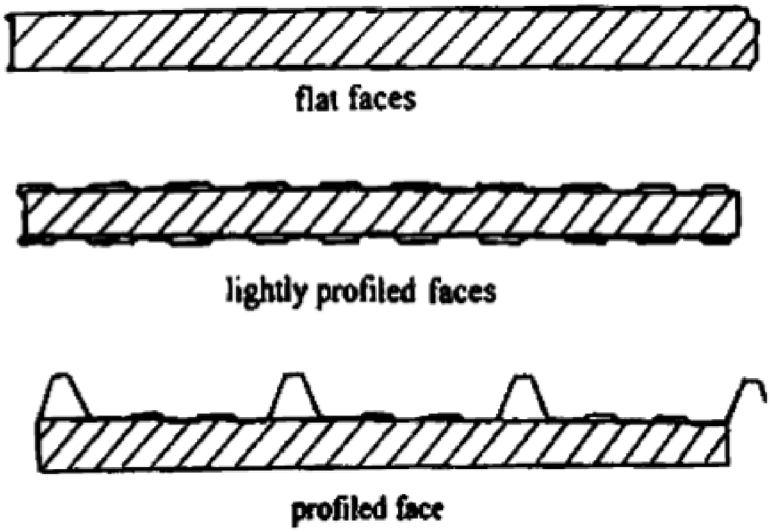


Figure 5: *Different faces (Mahendran & Pokharel 2003)*

European recommendations for sandwich panels describe different faces of panels. The faces of the panel are listed as lightly profiled if the rib depth is less than 3 millimeters. Microprofiled face is a term that is used to refer to a panel with constantly curving face sheets. Distance between the top and the bottom of the face should be from 0.5 to 3 millimeters. (European Recommendations for Sandwich Panels 2000)

Profiled face changes the behavior of the sandwich panel under load, because effective thickness is higher. Profiled faces are mainly used in in roofs and ceiling when higher strength is needed. (EN 14509:2013)

EN 14509:2013 specifies requirements for sandwich panels used as roofs and roof claddings, external walls and wall claddings and walls and ceilings inside the external walls of a building. Common for all aforesaid applications is the insulation between the metal faces and the panels are the factory made and self-supporting structures.

The European standard gives strict terms for the materials which are used in the faces and the core. All material properties have to be tested and standardized before material can be used in a sandwich panel. This limited usable production methods to few and this is the reason why the manufacturing process of construction sandwich panels is quite similar between the different manufacturers and variation in sandwich panels is quite small (Davies et al. 2001)

The whole manufacturing process is usually a long line, shown on Figure 6. The process is easy to cut into different parts but the general principle is that the face sheets and the core move on separate layers before adhesive.

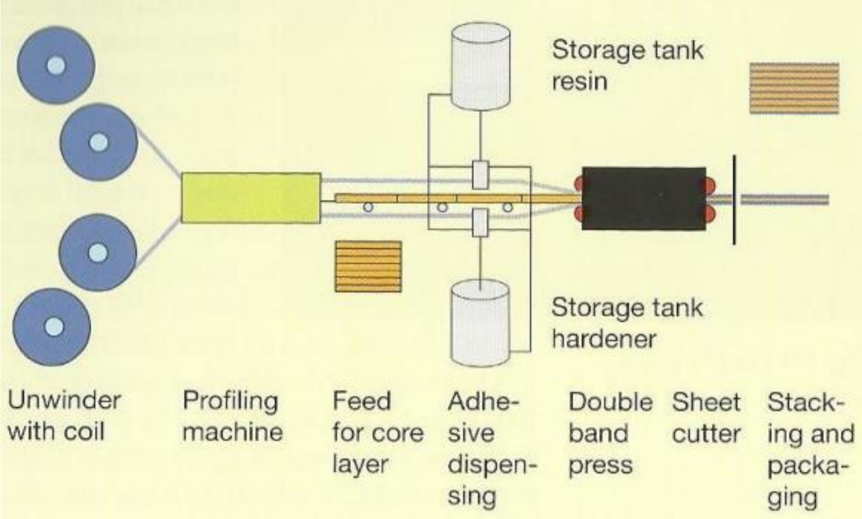


Figure 6: *Sandwich production generally (Thiele 2007)*

The face material comes from sheets or coils. If the coils are used, an unwinder is also needed. The process usually has at least two coil places per the face sheet because that ensures a coil changing without too long breaks. If metal sheets are used, some kind of seaming is needed before the adhesive. (Thiele 2007)

Face sheets are also profiled before the adhesive. Profiling can be done to both faces or just to one. The width of the metal in coils should be wider than the final width of a panel because profiling and formed edges reduce the effective width of the face sheet compared with the flat sheet.

All formation to the edges and profiling is made by using cold forming methods. Forming contains folding, press braking or roll forming depending on what kind of form is needed. Edges of face sheets are generally formed before adding the adhesive.

Next part of the process is the feed of the core. This part of the process varies much depending on the core type. The foamed core is mainly polyurethane (PUR) or polyisocyanurate (PIR). It ensures good thermal insulation and the bond with faces. High-pressure foaming units are widely used. (Davies et al 2001)

PUR foams are formed through the reaction between polyol and iso-cyanate, tri-chlor-fluor-methane or carbon dioxide is used as a blowing agent. Reaction generates heat and it vaporizes the blowing agent from the final form.

PUR foams are one of the cheapest materials that are used in cores of sandwich panels. PUR also have good insulation properties and they can be fire-resistant with additives containing phosphorus. (Zenkert, 1997)

PUR components start a chemical reaction which leads first to foaming and in the end to hardening. Before hardening, foam makes a strong bond with every surface it comes into contact.

Foamed cores can have different properties which can be achieved by using different recipes, additional components and changing time of reaction phases. The shapes of the sandwich panel come from the used mould. The mould is closed and its' dimensions are designed to be the same as the final product's. The lower face sheet is laid on the mould and upper sheet placed in a position supported on spacers after spreading foam.

This mould technique is usable in small scale production. In mass-production continuous automatic foaming lines are used. Foaming reactions generates pressure and in both techniques require a part after foaming where the face sheets are kept at the required distance apart. The continuous foaming line is presented on Figure 7. (Davies et al. 2001)

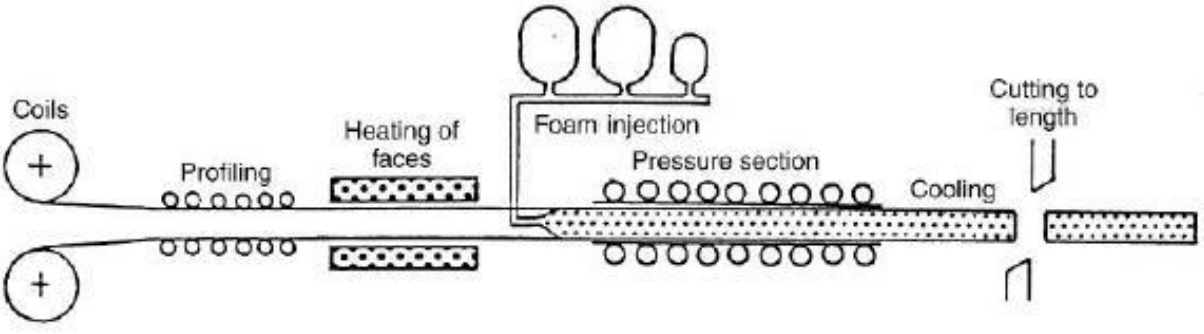


Figure 7: *Continuous foaming line (Davies et al. 2001):*

Other way is to use mineral wool as core material. Mineral wool properties vary depending on the orientation of mineral wool. Generally, mineral wool is cut from bigger sheets to right size lamellas and then rotated 90 degrees and pressed together before adding the adhesive dispensing.

A press is also used with the mineral wool core to ensure bonding. The pressure section of the production line generates uniform pressure to both sides of the sandwich panel. Functional bonding requires also right temperature and correct humidity. All these are controlled during the adhering process.

Final parts of the manufacturing process are cutting, stacking and packaging. Usually all parts of the process are automated with larger scale production. (Davies et al. 2001)

3. MATERIALS OF SANDWICH PANELS

3.1 Material requirements

The purposes of the sandwich structure determinate properties which are wanted from the materials. Different materials and core structure is needed if sandwich panels are for example mainly used for insulation, against rain and fire or to resist mechanical loads. (Kepeng, Q.I.U, 2008)

Several important mechanical properties of the face sheets and core must be achieved before sandwich structure works technically right. The sandwich panels are under bending during and after construction and bending can also affect wrinkling to the face sheets. Therefore the face sheets have to be stiff and strong in tension and compression so that the structure is strong enough against bending and wrinkling.

Bending loads generate deformation to the whole panel. The face sheet which is on the same side as the load is under compression and other face sheet is under tension. This is explained in Figure 8. The loads also have an effect on the core. The largest stress of the core is the shear stress. The core needs to be strong and stiff against it. To get the full advance from using the sandwich structure, the core needs to be also light weight (Carlsson & Kardomateas 2011)

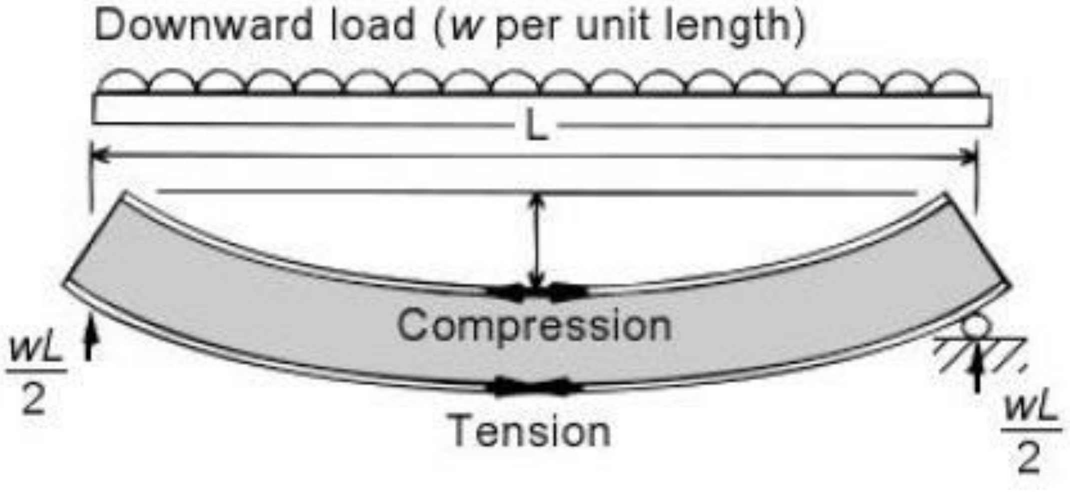


Figure 8: *Effects of loads in the face sheet (Davies et al. 2001)*

Both, the core and the face sheet need capacity to resist non-mechanical actions like moisture, corrosion and fire. The face sheets must be dense to protect the core layer.

Sometimes some extra layers are added to the sandwich panel to gain better fire protection.

Materials need to be chosen to meet the manufacturing requirements. As mentioned earlier, manufacturing of sandwich panels is well standardized and only a few different modifications can be found. The face sheet material should be bendable without the risk of breaking. Metals are the most economic material for the faces, they must be easily profiled by roll forming and then the metal face manufacturing process is can be arranged to be almost continuous. (Davies et al. 2001)

SFS-EN 14509:2013 gives guidelines to material choosing. All materials used together in a sandwich panel have to meet the requirements specified in EN 14509. Different Euronorms defines requirements just for material used in panels. Final products have to be made to meet all these requirements.

3.1.1 Steel material properties and regulations

As mentioned earlier, the face sheets work under tension and compression. Stiff and strong homogeneous material is needed and different metals are the best option for that.

When normal steel is used, a corrosion protection layer is needed. Without the corrosion protection layer, rust destroys quickly aesthetic of the panel and later also weakens mechanical properties. It is possible to do the corrosion protection using different techniques. One of the easiest is metal coating placed over steel substrate, shown on Figure 9. The steel is hot-dipped pure zinc, zinc-aluminum or aluminum-zinc before rolling. Protective film can be added after dipping.

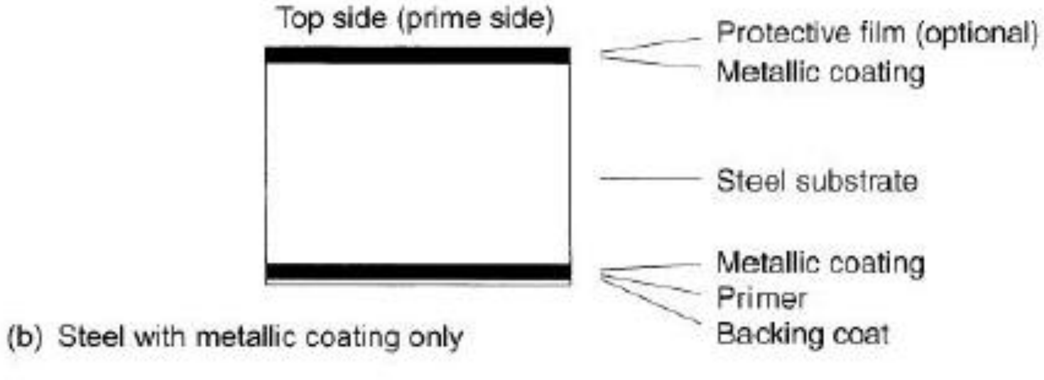


***Figure 9:** Steel with the metallic coating layer (Davies et al. 2001)*

Zinc layer itself normally does not provide durable corrosion protection and another layers is needed. Sandwich panels with zinc coating also looks quite ugly and good aesthetic appearance is harder to achieve. The bond between the core and the face sheet is weaker if the surface of the sheet contains only a zinc layer.

These are the reasons why additional organic coating layers are often added. A primer is recommended before organic coating. The primer ensures the good bond between coatings and final organic coating is usually added instantly after the primer because adherence arises easier when the primer is still fresh. Figure 10 is the steel face with the organic top coating.

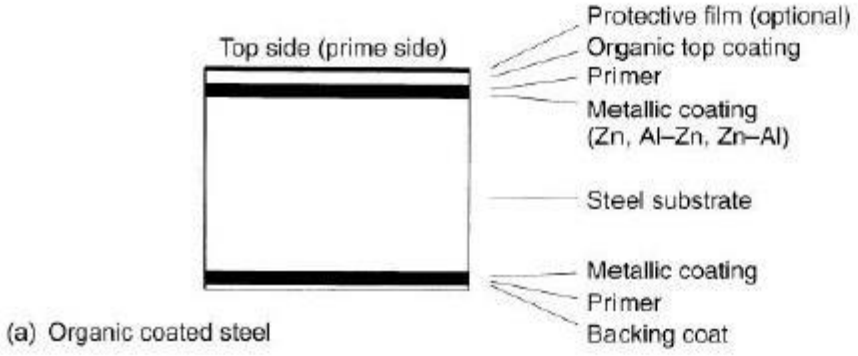


Figure 10: *cross-section of steel face (Davies et al.2001)*

Coatings are not calculated to the effective thickness of the face sheets and this should be noticed when determining the proper design thickness. Coating layers increase the whole thickness of the face sheet and amount varies depending on how strong corrosion protection is wanted. (Davies et al. 2001)

The recommended minimum thickness of coating is determined in EN 10214 and EN 10215. In sandwich panel manufacturing metal sheets come as coils or sheets and the coatings are added by metal manufacturing. Possible face sheet materials are presented in Table 1

Table 1: *Material specs of the face sheets (EN 14509:2013)*

Material	**Minimum yield strength**	**European standard**
Steel	220 N/mm^2	EN 10346
Low-carbon steel	300 n/mm2	EN 10142
Stainless steel	220 N/mm^2	EN 10088-1, EN ISO 9445
Aluminum	140 N/mm^2	EN 485-2, EN 1396
Copper	180 N/mm^2	EN 1172

Sandwich panel standard EN 14509 gives a list of possible face sheet materials. However, steel is normally the most used material because it is economical and in many ways it is easier to use than other metals.

3.1.2 Core material properties and regulations

Core materials have to resist mechanical loads and work as insulation and resist fire. Typical core materials are mineral wool, polystyrene (EPS or XPS), Polyurethane (PUR), Phenolic (PF), Cellular glass or polyisocyanurate (PIR).

EPS and XPS, PUR, PIR and PF are chemically formulated foams. It is possible to spread PUR and PIR between the face sheets and adhesive is not needed. Foam itself makes a good bond under the right circumstances, which have to be ensured during the manufacturing process. Moisture and temperature are things which affect bonding. (EN 14509)

If thermal insulation is the main targeted characteristic, then rigid plastic foams are often used as core materials. Foams can have many different material properties depending on the raw material used. It is also possible to change the foam properties by changing details of the recipe or manufacturing process. Final forms of foams can be divided into four groups: open or closed cell structure or in rigid or flexible foam.

However to achieve all required properties, the core is normally made from rigid foam material with pre-dominantly closed cell structure. The most commonly used materials are listed earlier in this chapter.

Rigid foams are a good choice because they have low density and still quite good mechanical properties. The lowest density with required physical properties is wanted because the cost of raw material is more significant than the cost of manufacturing.

Material of the core can also be inorganic fibre material as glass wool or stone wool. Mineral wool cores are built from prefabricated slabs which are bonded to the faces using an adhesive. Inorganic fibres are chosen when fire security is needed. (Davies et al. 2001)

All mineral wools are porous materials. The structure is normally really fractioned and volume of air inside can be over 95 percent. Fibers are usually few millimeters long and their diameter is about ten micrometers. Fibers are joined together with the binder and its amount is typically 1-10 percent of total weight of structure. (Reentilä 2003)

Mineral wool has different mechanical properties depending on in which direction these are measured. The reason for that is the manufacturing process which orients fibers.

Both, glass wool and stone wool production includes melting, fiberizing and curing. The basic materials of glass wool are sand, soda ash, limestone, dolomite, sodium sulphate sodium nitrate, minerals containing boron and alumina and waste glass. Stone wool traditionally contains the combination of alumino-silicate rock like basalt, blast furnace slag, and limestone or dolomite. It can also contain recycled process or product waste. Figure 11 shows the manufacturing process for both glass and stone wool.

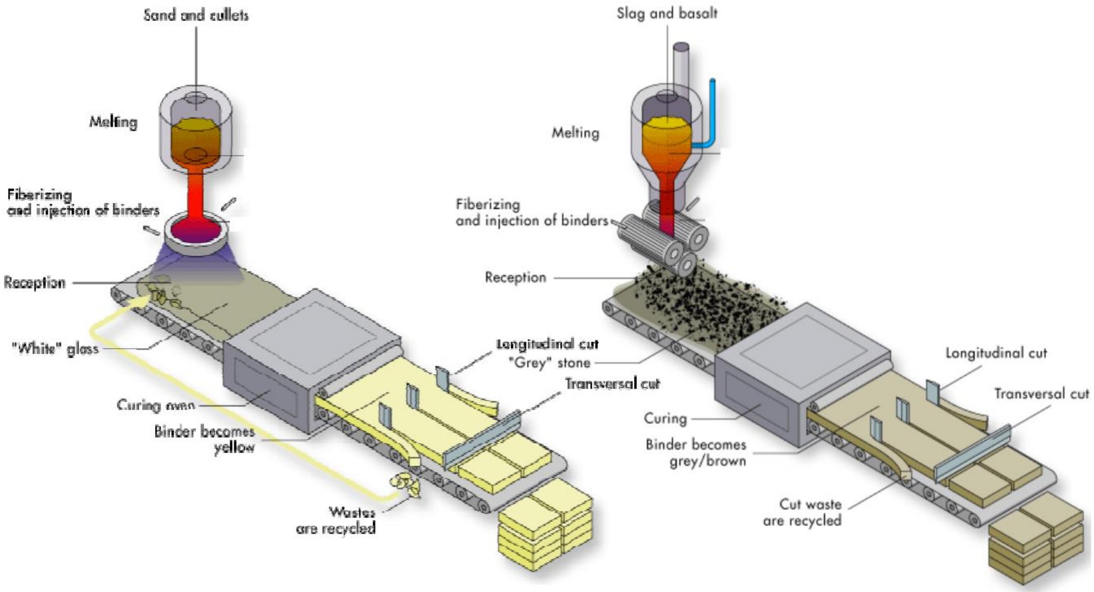


Figure 11: *The manufacturing process of mineral wools ((Fraunhofer Institute for Systems and Innovation Research 2009)*

Both processes have a general plant configuration which starts with melting. Then melted raw material is fiberized and binders are injected. Fibers are laid on a conveyor, compressed and cured, and then wool is cut to slabs. It is possible to melt cut waste again. (Fraunhofer Institute for Systems and Innovation Research 2009)

Glass and stone wool are quite similar products. The main difference is that glass wool has a lower melting point and it contains more binder. Its amount varies between 4 and 15 percent of the total weight of glass wool. In both mineral wool types, it is possible to add oil to make the structure more water resistant.

The manufacturing process makes all mineral wool products very orthotropic. Longer fibres are aligned along a conveyor. Their orientation remains during the whole process and in the final product. Shorter fibres have random orientation making wool slabs stiffer and stronger in their own plane. The fibres act as elastically supported small columns in the stiff direction and in the other direction like elastically supported small beams. The bonding agents are derivers of stiffness and strength in the wool slabs.

Even though mineral wools do not have to have high tensile, a shear or a compressive strength in a direction normal to their length, they can be used as a core after turning.

Before turning slabs are cut into lamellas with a width equal to the required height of the core. This is the way to ensure the fibres are orientated correctly. The process is shown on Figure 12

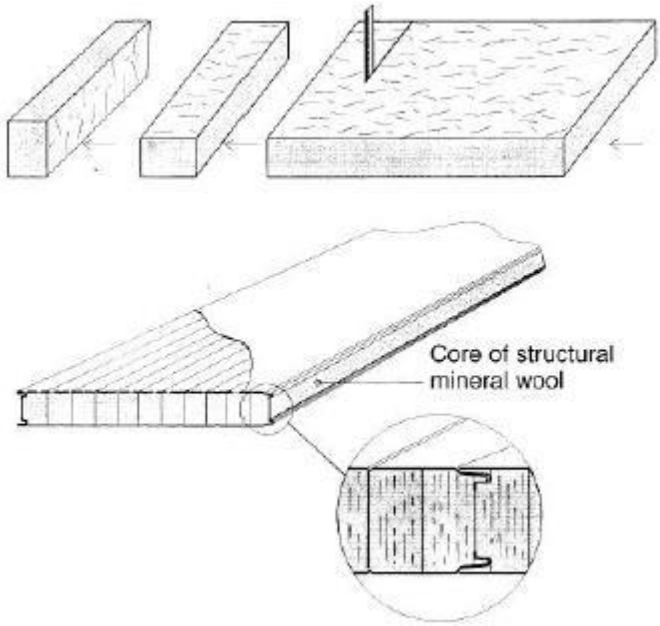


Figure 12: *Mineral wool slabs (Davies 2001)*

During the rotation, it is important that all lamellas have the same height and their faces are flat. The mineral wool used in sandwich panels usually has 70 kg/m^3 density but it can be high as 150 kg/m^3 depending on the fire safety requirements.

Some typical levels of the structural mineral wool properties are listed below in Table 2. Mechanical strengths are related to density but the variation of strength values can be substantial even in the same density.

Table 2 : *The mechanical properties of mineral wools*

Density [kg/m^3]	Compression strength [N/mm^2]	Tensile strength [N/mm^2]	Shear strength [N/mm^2]
70-150	0,06-0,15	0,03-0,3	0,03-0,2

Mineral wools have a little bit different thermal abilities compared with closed cell foams. Mineral wool has open structure, where the thermal conduction of air happens and heat flow is greater. The thermal flow in mineral wool is mainly caused by the conduction of air, about 75 %, and the conduction in fibres causes about 20 % and the rest 5% is due to radiation. The orientation of mineral wool affects thermal flow and lamellas have higher thermal conductivity than slabs.

The fibres and binder do not themselves absorb any water but because the structure is open and has plenty of space, about 95 % is air-filled space. The space can absorb a huge amount of water if circumstances allow it. In a normal situation, the face sheets of the sandwich panel protect the core and water absorption is 0.2-0.5 %. It can be reduced by using additives, mainly silicon or mineral oil. Stone wool has the lower water absorption than glass wool because their internal structures are different. Water-absorption is nevertheless unwanted and water resistance plays the huge role in the final production. (Davies 2001)

The properties of primary interest for the core can be listed as:

- Low density
- Shear strength
- Shear modulus
- Stiffness perpendicular to the faces
- Thermal insulation

This list applies for the most commonly used core materials in structural sandwich panels. (Zenkert 1995)

3.1.3 The adhesive properties and regulations

The adhesive layer makes a sandwich panel work as planned. The bond between the core and the faces transfers loads from one layer to another and prevents unwanted movements between the core and the face sheet. By mechanical properties, the adhesive’s values should be at least as good as the core material’s. That is the way to ensure the strength of the bond and that it is not the weakest part of the panel.

In other ways, the adhesive can have and it usually has a complex structure which is quite different than the core material. The bond in panels with mineral wool mixes with the core material and together they form an adhesive zone. The zone is formed by the glue which penetrates to the core and forms a mixture of glue and core material.

Some requirements are mentioned for the glue and gluing. It should be easy to spread ether on the core or on the surface of the face sheet to be bonded. After spreading glue, the bond has to form quickly enough. Adhesives require the exact right temperature and humidity to work properly and these requirements should be considered in the manufacturing process. (Davies et al. 2001)

Two-component glues are some of the most used adhesives. Polyurethane is usually the best option because it works fast and creates a strong bond. It can also be used as the core material but then the recipe is different.

The main ingredients of polyurethane are isocyanates, polyols and some additives are also used to increase some features of the final product. Polymer formation can be really rapid and sometimes catalysts are used to control the reaction time.

Isocyanate molecules have to contain at least two isocyanate groups $(- N = C = O)_{n \geq 2}$ which can react and form a chain with the other isocyanate groups with a polyol molecule in between them. Like isocyanate, polyol molecules also have to contain two parts which react with each other. These parts are called hydroxyl groups $- (OH)_{n \geq 2.}$ Figure 2Figure 13 shows the chemical reaction between di-isocyanate and polyol.

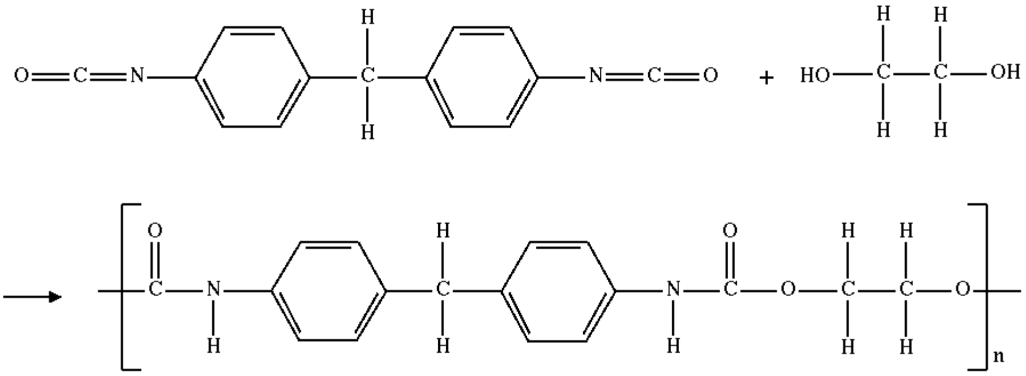


Figure 13: *Chemical reaction of polyurethane*

Polyurethane reaction generates heat and the reaction warms propellant gas and forces it to expand. At the same time polyurethane expands and forms foam. However, this foam formation depends on what kind of polyols and isocyanates are used and additives can also prevent the mixture from foaming. (Hepburn 2012)

Loctite UK 8596 and Loctite UK 5400 are examples of products that are used in sandwich panels. It is solvent-free two-component foaming polyurethane adhesive. The resin part contains organic compounds with hydroxyl groups and the hardener contains isocyanates. The mixing ratio by weight is 1:1.

The used mixture and its components have to be chosen by the produced panel type. It is possible to control the opening time of the mixture a little by adjusting the temperature and the moisture. (Henkel 2011)

The foaming of polyurethane is desirable because the foam ingresses mineral wool and makes a deeper bond between it and the face sheet. A good bond usually contains mineral wool mixed well with polyurethane and the whole structure breaks if one tries to remove the face sheet. (Davies et al. 2001)

4. MECHANICAL BEHAVIOR OF SANDWICH PANELS

4.1 Stresses in a sandwich panels

As earlier mentioned, material choices change greatly the technical and mechanical properties of sandwich panels. The material and dimension choices should be made according to the final purpose of the panel. External panel elements have different requirements than panels used in cold storages, for example.

Loads are divided differently to sandwich structure. The faces take almost entirely the compression and tensile forces. If the sandwich panel has flat or lightly profiled faces, bending moments change to the axial forces of the faces. However, if the face is profiled, it can carry also the bending forces. The reason is that profiled face has significantly larger bending stiffness than flat faces. (Mahendran & Pokharel 2003)

Sandwich panels have some uncommon requirements during loading and stress calculation compared with other forms of construction. Core material is usually malleable in structural sandwich panels and shear forces deform it easily. The shear deformation should be considered when stress resultants are determinated.

It is possible to estimate that core and face materials behaves linearly elastic for the range of deformations that are reasonable to take into account. Other assumption is that longitudinal normal stresses have minimal impact on the core, because the core has much smaller extensional stiffness than the faces. The influence of longitudinal normal stresses in the core can be safely left out in load bearing checks.

The load bearing capacity of a sandwich panel can be divided into two components in a panel with flat or lightly profiled faces. Figure 14 shows this very simple situation where the bending stiffness of the faces is small and can be neglected in the analysis.

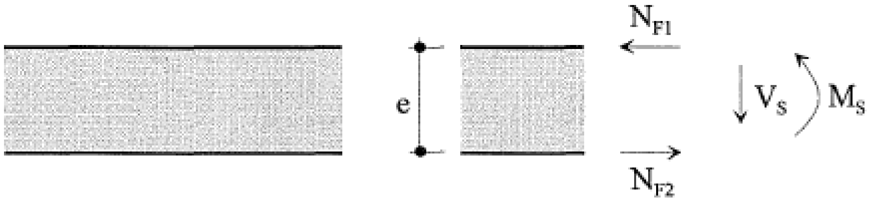


***Figure 14:** Stress resultants in a sandwich panel (European Recommendations for Sandwich Panels 2000)*

The calculations can be based only on the stress resultants M_s, N_{F1}, N_{F2} and V_s. Bending moment M_s is possible to calculate by using the equation 4.1.

$$M_s = eN_{F1} = eN_{F2} \tag{4.1}$$

where e is the distance between the centroids of the faces and N_{F1} and N_{F2} are normal forces. Normal force N_{F1} causes uniform compression stress σ_{F1} to the external face and in turn, N_{F2} causes uniform tensile stress σ_{F2} to the internal face. Stresses in the faces can be expressed with the equation 4.2 and 4.3 (European Recommendations for Sandwich Panels 2000)

$$\sigma_{F1} = -\frac{N_{F1}}{A_{F1}} \tag{4.2}$$

$$\sigma_{F2} = \frac{N_{F2}}{A_{F2}} = \frac{M_s}{eA_{F2}} = \frac{M_S}{eh_f B} \tag{4.3}$$

Calsson and Kardomateas present the same using the equation (4.4) to express an average bending stress in the face sheets when the sandwich panel is under pure bending loads.

$$\sigma = \frac{M}{Beh_f} \tag{4.4}$$

where M is the bending moment. The distance between the centroids of the faces is e, h_f is the thickness of the face sheets and B is the width of the sandwich panel. (Calsson & Kardomateas 2011)

Shear force V_s causes shear stress τ_c over the depth of the core. The stress is constant if compressive and tensile rigidity of the core layer is ignored in the longitudinal direction of the sandwich panel. This assumption can be done because the core has significantly smaller values than the faces. Shear stress can be expressed using the equation 4.5. (European Recommendations for Sandwich Panels 2000)

$$\tau_c = \frac{V_s}{eB} \tag{4.5}$$

All stresses are shown on Figure 15. Notable things are compression and tensile stresses appearing mainly in the face sheets and the shear in the core.

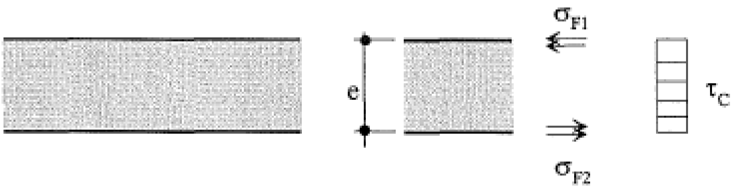


***Figure 15:** stress distribution over the cross-section in a flat of lightly profiled panels (European Recommendations for Sandwich Panels 2000)*

Situation where there is tensile or compression stress only on the face sheets happens with single span sandwich panels. With continuous multi-span panels stress can change from tensile to compression and back depending on loads. If load, usually wind load, bends panels inward, appears tensile stress in the external face and compression in the internal face in the middle support.

4.1.1 Compression and tensile in the core

The face sheet does not have much effect on compression or tensile tests. Loads are orientated orthogonal to the surface of the panel and the core reacts first because it is more fragile. Other reason is that faces are usually made from solid material.

The primary loads of sandwich panels are located on the supports and near the supports. In this situation, the loads are orientated straight towards or outwards from the panel. Possible loads are snow, wind load, a walking person as a point load and hanging loads from the ceiling. Secondary loads can come from any direction.

Fasteners can affect compression if they are screwed too tight. Tensile appear in situation where fasteners attach a heavy projection to the panel and the projection tries to pull the fasteners out from the panel and the fasteners pull the face sheet away from the core in turn. (European Recommendations for Sandwich Panels 2000)

Wind cause compression only to those parts of the panel which have a support behind them. Support reaction causes a stress which is divided uniformly and expanding from support to mid-depth of the core. This is shown on Figure 16

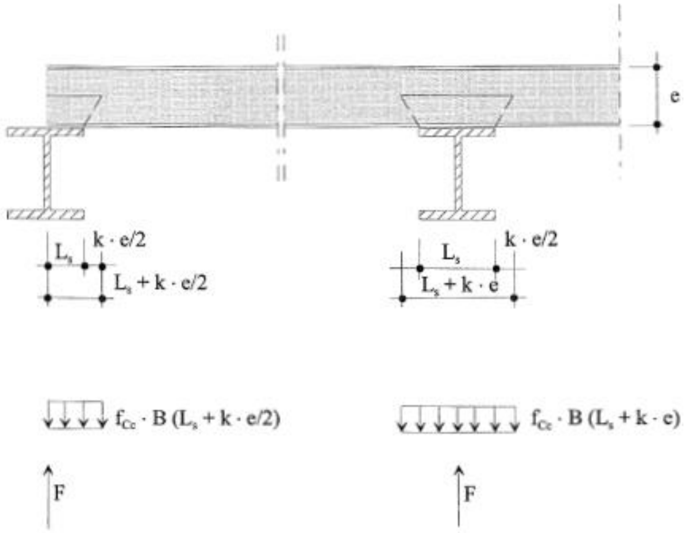


Figure 16: *support reaction and stress (European Recommendations for Sandwich Panels 2000)*

Support stress affects different core materials differently and each panel type has its own angle of dispersion of $\tan^{-1}$ (k), where *k* means the distribution parameter. European recommendations for sandwich panels advices to determine it experimentally. If the core is mineral wool, it is possible to choose k =0. Loads are divided a little bit differently at an end and an intermediate support. Compressive stress on the end support is:

$$\sigma_{Ccd} = \frac{F}{B(L_s + ke/2)} \tag{4.6}$$

Compression stress on the intermediate support is:

$$\sigma_{Ccd} = \frac{F}{B(L_s + ke)} \tag{4.7}$$

Where *F* is support force, *B* is the width of the panel, L_s is the length of the support, *e* is the distance between the centroids of the face sheets and *k* is the distribution parameter. (ECCS 2000)

4.1.2 Shear deformation of a sandwich panel

The shear deformation of the core can be approximately calculated with the method described in Structural and Failure Mechanics of Sandwich Composites by Carlsson and Kardomateas. They combine different theories in their model. Next equations are from their book.

Some assumptions are needed before the analysis works well. The coordinate system *xyz* is originated to the center of the core and in the core mid-plane z = 0. The core is much thicker than the face sheets. In the face sheets, the in-plane displacements, u and v are uniform through the thickness of the face sheets and assume their centroidal values. In the core, u and v are assumed to be linear in the thickness coordinate z.

The in-plane stresses on the core should also be so small that they do not have an effect on calculation, i.e. $\sigma_x, \sigma_y, \tau_{xy} = 0$. Also the thickness strain, $\varepsilon_z = \partial w / \partial z = 0$, then the out-of plane displacements, w, is independent of the z coordinate.

The displacements of the core can be described with the next equations:

$$u = u_0(x,y) + z\psi_x\,(x,y) \tag{4.8}$$

$$v = v_0(x,y) + z\psi_y\,(x,y) \tag{4.9}$$

$$w = w_0(x,y) \tag{4.10}$$

where u_0 is the displacement in x-direction, v_0 is the displacement in y-direction and w_0 is the displacements in z-direction. ψ_x and ψ_y are the rotations of the cross section. Shear deformation is shown on Figure 17. Upper picture shows situation before deformation and lower after deformation.

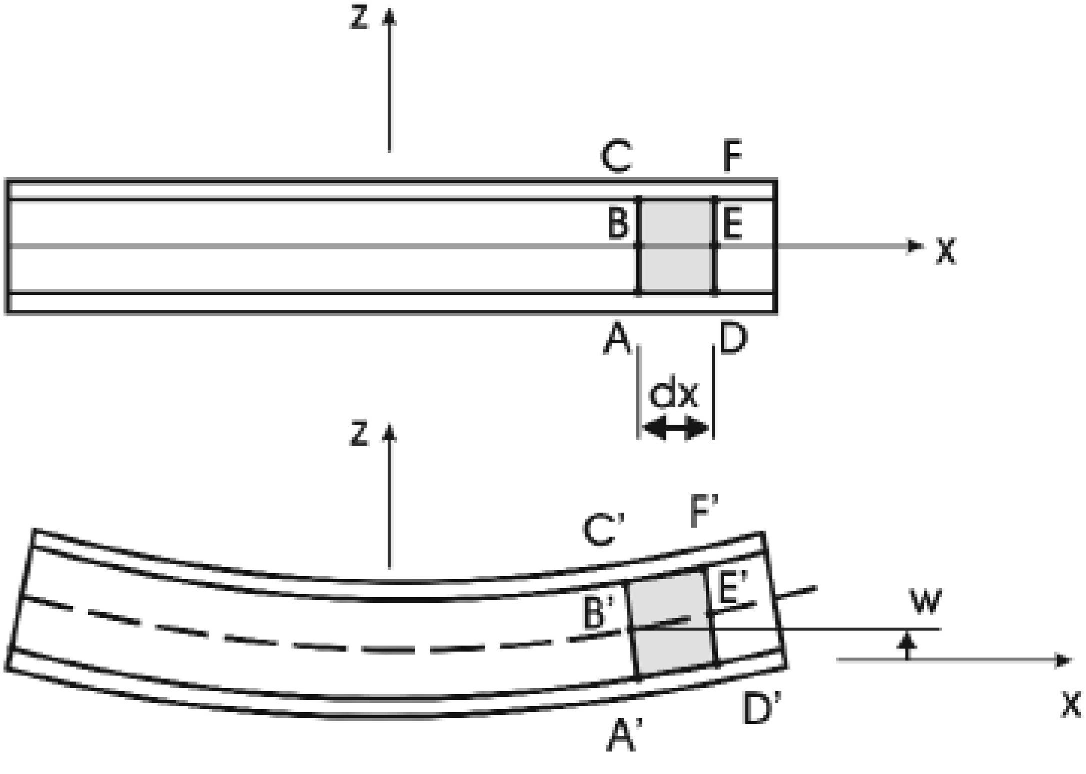


Figure 17: *Deformation of a sandwich panel (Calsson & Kardomateas 2011)*

With the core element ACFD it is possible to describe deformations. Before deformation point B is original at x-plane where z = 0. The shear deformation displaces B to new point B’ and the vertical upwards displacement is *w* and the new position is z = w. Point E is also originally at x-plane and after deformation the new position E’ is z = w + (*∂ w/ ∂ w) dx.*

The shear forces deform the rectangular core element and point E’ rotate first with the whole cross-section the magnitude of the rotation ψ_x and the difference β_x. The whole displacement of point E’ can be described with the slope of the middle surface and it is *∂ w/ ∂ x*. This is shown better on Figure 18

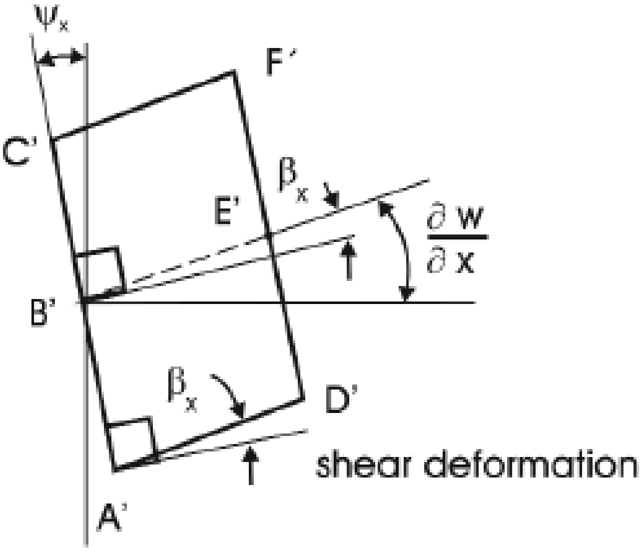


Figure 18: *Shear deformation (Calsson & Kardomateas 2011)*

The difference which comes from shear deformation can be calculated by using the equation:

$$\beta_x = \frac{\partial_w}{\partial_x} - |\psi_x| \tag{4.11}$$

4.1.3 Shear modulus

A shear modulus of material tells how much material resist shear deformation. The basic equation for shear modulus is the equation 4.12:

$$G = \frac{\tau}{\gamma} \tag{4.12}$$

where τ is shear stress and γ shear strain. (Calsson & Kardomateas 2011)

Shear stress can be calculated by using equation 4.5 but shear strain γ can be challenging to measure. Different test methods have different equations for shear modulus and they are described in Chapter 5.

4.1.4 Wrinkling stress in the face sheet

As earlier mentioned, the stresses on the faces can be calculated by using equations 4.2 and 4.3.The wrinkling stress can be calculated more accurately by using different equations. These equations are shortly introduced next. However, they work well only when the calculated wrinkling stress is in the sandwich panels with foam cores.

For the wrinkling stress in flat and lightly profiled panels, it is possible to use the equation 4.13:

$$\sigma_{wr} = \frac{1{,}89}{A_f}\left[\frac{8(1-\nu_c)^2 E_c G_c B_f}{(1+\nu_c)(3-4\nu_c)^2}\right]^{1/3} \tag{4.13}$$

where A_f is a cross-sectional area of the face sheet per unit width, υ_c is Poisson’s ratio of the foam core, E_c is the modulus of elasticity of the core, G_c is the modulus of shear of the core and B_f is the flexural rigidity of the lightly profiled face sheet, it can be expressed with the equation 4.14:

$$B_f = \frac{E_f I_f}{b} \tag{4.14}$$

where E_f is the modulus of elasticity of the face sheet, I_f is the moment of inertia of the face sheet and b is the width of the element. Equation 4.6 makes the wrinkling stress calculation possible but usually this method is too complicated and time-consuming to be used in practice. (Mahendran & Pokharel 2004)

European recommendations for sandwich panels also recommend that the wrinkling stress is determined on the basis of tests. It nevertheless gives the equation to calculate the wrinkling stress:

$$\sigma_{wr} = \frac{k_p}{A_f}\sqrt[3]{E_{cT} G_{cT} E_f} \tag{4.15}$$

where k_p is constant and its value depends on the imperfections and quality of the face, core and bond. The values of k_p are determined experimentally and it can vary from 0.65 to 0.95. The subscript T in equation 4.15 means that calculation is possible at bot ambient and elevated temperatures. (European Recommendations for Sandwich Panels 2000)

When equation 4.15 is used (when k_p is 0.95), it gives values which are approximately 50 % smaller than the values of equation 4.13. The values are reduced, because some practical limitations are included in the calculation. Such limitations are, for example, finite depth and non-linear behavior of the core, the bond between the face sheet and the core and imperfections in the face sheets.. (Mahendran & Pokharel 2004)

4.2 Failures of a sandwich panel

Like all structures, sandwich panels have a maximum load carrying capacity which is shown with ultimate limit states and serviceability limit states. The sandwich panel's different failure modes are described in the European Recommendations for Sandwich Panels. The failure modes can occur individually or together. In this thesis only those failure types are shown which may appear during the tests.

The tensile failure is a quite rare failure mode in structural sandwich panels because they usually have metal face sheets. Typically, the metal sheets have high yield stress and tensile strength and wrinkling or shear failure of the core happens first. Tensile failures can appear at the mid span or at the intermediate support; this is shown on Figure 19

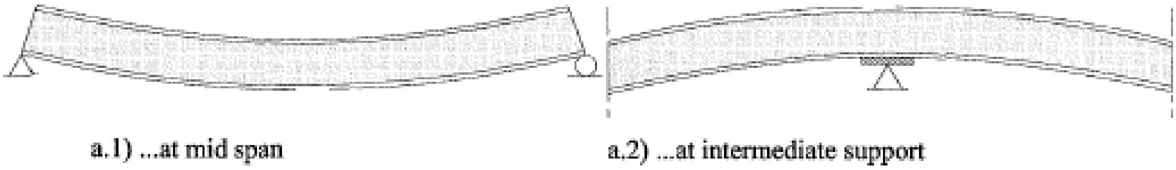


Figure 19: *Tensile or compressive strength of the face by yielding (European Recommendations for Sandwich Panels 2000)*

A much more common failure mode for the face sheet is a wrinkling failure. In some point, stress in a compressed face raises to high and wrinkling appears. When this happens, depending on the thickness of the sandwich panel layers, the profile of the face sheets and the stiffness and the strength of the core material. (Davies et al. 2001)

Different loadings affect local elastic wrinkling waves to the faces of the sandwich panel. In the flat faces this leads soon to wrinkling under axial compression and/or bending actions. The wrinkling failure is shown on Figure 20.(Mahendran & Pokharel 2003)

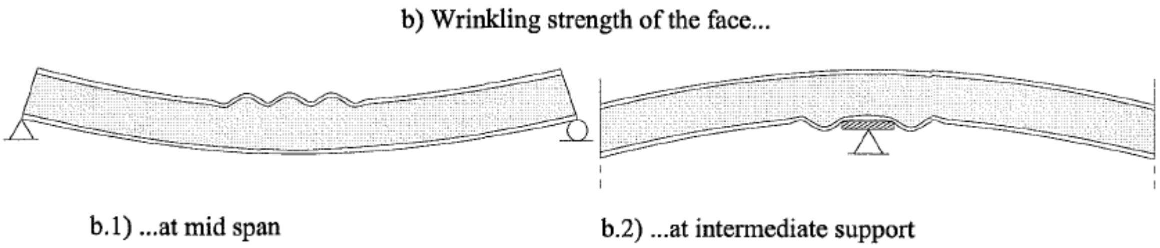


Figure 20: *Wrinkling failure (European Recommendations for Sandwich Panels 2000)*

The shear loads are carried mainly by the core and shear failure appears in the core or in the bond between the core and the face sheets. The center of the core is weaker in rigid foam cores and shear failure usually starts from there. Typical shear failure forms are found on Figure 21.

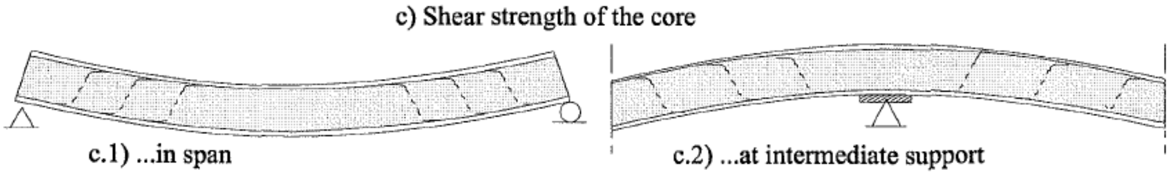


Figure 21: *Shear failure (European Recommendations for Sandwich Panels 2000)*

Last failure mode which might have an effect during testing is the crushing failure on the support. Crushing failure happens when support size is quite small and loads are big enough. This failure is shown on Figure 22. (Davies et al. 2001)

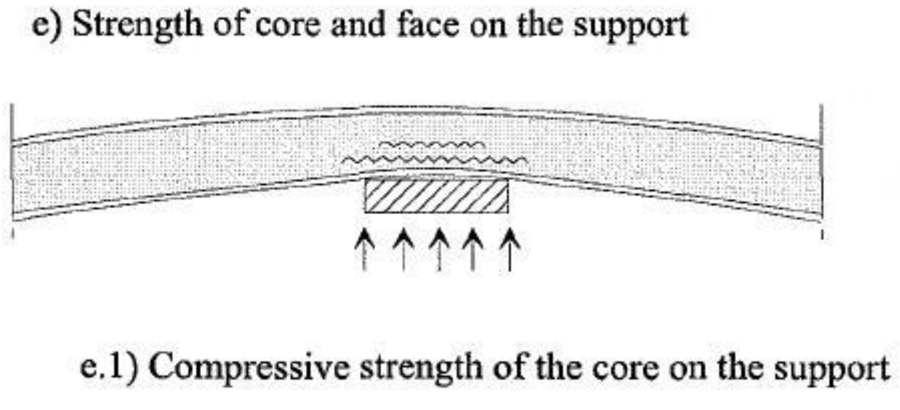


Figure 22: *The crushing failure on the support (European Recommendations for Sandwich Panels 2000)*

All these failure types can appear in the test. However, the goal is determinate the shear strength, and only the shear failure is wanted. In testing, it is possible to try to avoid the unwanted failure modes by choosing right dimensions for the supports, the span and the load areas. Test arrangements are described in the next chapter.

5. TESTING PROCEDURES

5.1 Possible testing procedures to determinate shear properties

Different test methods were developed to test mechanical values of sandwich panels. Some of them work better than others and give more accurate values. Especially, the shear strength and shear modulus of the core was challenging to measure because different core materials behave differently under load. Different test methods are described next; but some of them are not used anymore.

Loading a short strip of the sandwich panel in four-point bending was the recommend method for the rigid plastic foam core. For mineral wool cores, the best way is to use full-scale panel tests. Possible test methods are described below. (Davies et al. 2001)

The plate shear test was previously used with thinner sandwich panels. The test method was also known as the ASTM standard C273 (2000). The test specimen could be cut from the sandwich panel or it can be just a piece of the core material. It was adhesively bonded to the loading platens, which were steel blocks. Then the blocks were loaded with tensile load *P* to produce shear loading in the test specimen. The method is shown on Figure 23.

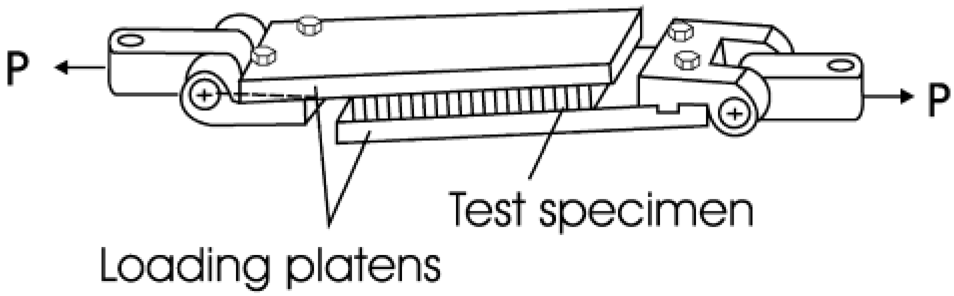


Figure 23: *The ASTM standard C273 plate shear test (Carlsson & Kardomateas 2011)*

However, this test method does not produce a pure uniform shear stress in the entire test specimen. The test specimen should be so long that the line of load passes through the diagonally opposite corners of the specimen. This line goes with the centers of pins at the end of steel blocks. If the line of load does not go like this, tensile load produces secondary stresses in the specimen. Pure shear strength is then harder to determinate.

In this test method, the width of a test specimen is recommended to be 50 mm or more. A length of the specimen should be more than 12 times the thickness and close to it that the line of load goes described above. The notable thing is the adhesive should be not-flexible. Otherwise it would affect the test results. Shear strength and shear modulus can be calculated when force P and displacement in the test specimen are measured.(Carlsson & Kardomateas 2011)

A similar test method is also described in EN 12090:2013 Thermal insulating products for building applications. Determination of shear behavior. Like ASTM standard C273, the EN 12090 test method does not give or determinate pure shear behavior. Test apparatus is shown on Figure 24.

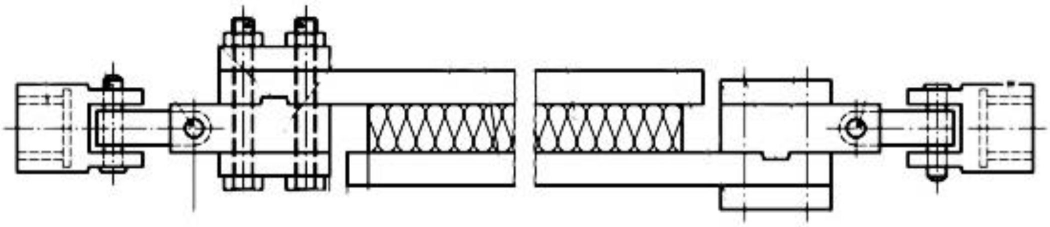


Figure 24: *One test specimen shear test method EN 12090:2013*

The force F on the test specimen and displacement should be measured during the test. Fixed machine grips should move away from each other to opposite directions with the uniform speed of 3±0.5 mm/min.

It is also possible to test two specimens at the same time with the similar test arrangements. The test apparatus is quite similar as the apparatus used for one specimen and it is shown on Figure 25.

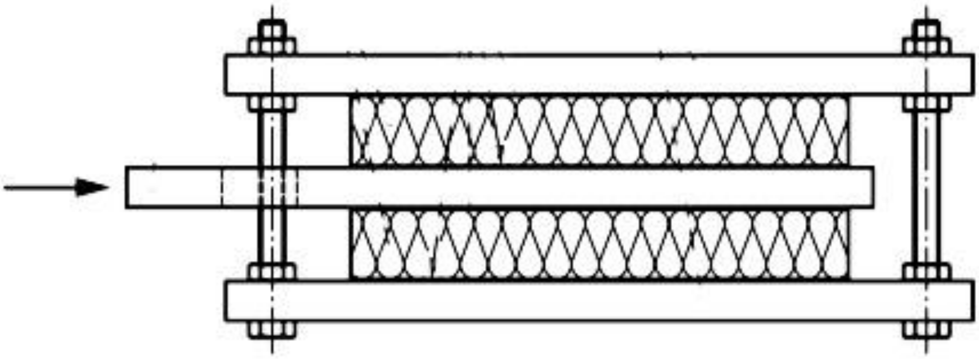


Figure 25: *Two test specimens shear test method EN 12090:2013*

The shear strength is calculated using the equation:

$$\tau = \frac{F_m}{A} \tag{5.1.}$$

Where F_m is the maximum load and A is area of the cross-section of the specimen. It is possible to calculate the shear modulus if the force-displacement curve is recorded. Example of the curve is shown on Figure 26.

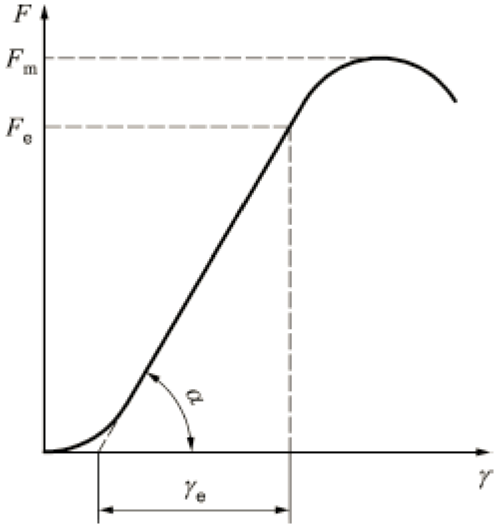


Figure 26: *The deformation/Force curve*

Usually, it is possible to find the straight portion from the force-displacement curve and calculated the slope *tan α* and then the shear modulus with the equation:

$$G = \frac{d \tan \propto}{A} \tag{5.2.}$$

where d is thickness of the test specimen. (SFS-EN 12090:2013)

One method is called “square test” and it works well with rigid foam cores. A rectangular prism is cut from the core of the sandwich panel. The prism usually contains a 100 mm x 100 mm cross section and a length larger than 100 mm and usually 150 mm.

In this test, it is important to cut a correctly orientated test specimen. Two of the 100 mm sides are recommended to be parallel with the faces of the sandwich panel and two others perpendicular to the faces.

After cutting, stiff plates are bonded with the adhesive to four similar sides of the prism. Now the test specimen is ready to be loaded with compression and tensile placed diagonally across the prism. Under loads the prism simulates situation in the panel and it should have the similar state of the shear stress as in a full-scale panel. (Davies et al. 2001)

At the moment, the most accurate test methods can be found in EN 14509:2013. There are two different test methods described, A.3 and A.4. The A.3 test method is shown on Figure 27 below. A.4 is a test method for the full scale panel testing.

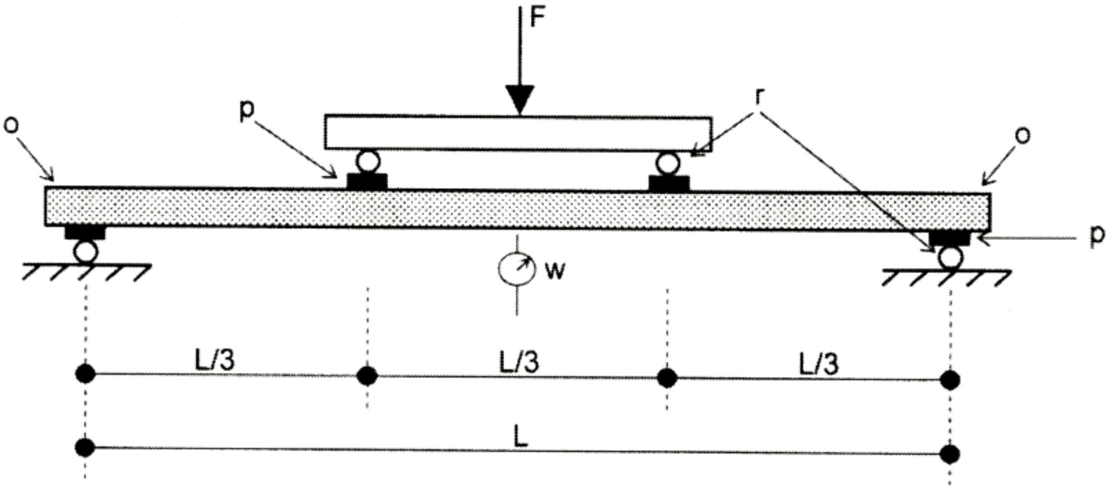


Figure 27: *a beam test method (EN 14509:2013, part A.3)*

A.3 test method is sometimes called a beam test method. The test specimen fails in shear when ultimate load is achieved. Displacement and load are measured and the load deflection curve is drawn.

During the test, the test specimen is loaded with a load from above and loads are divided to two points by using load spreading plates. The thickness of the plates should be between 8 and 12 millimeters and their minimum width at least 60 millimeters. Similar plates are also placed at the support points. The width of the plate can be increased if the test specimen does not fail because of shear but because of compression failure.

The span *L* depends on the thickness of the test specimen. EN 14509 recommends 1000 millimeters and reduces it gradually to 100 mm until shear failure happens. With mineral wool cores, the span should be greater than 1000 mm.

The width of the specimen should be over 100 mm if the core material is mineral wool and the recommended width is the width of the lamella. With other core materials, 100 mm width is normally enough. The test specimen should not contain cut ends of lamellas.

After shear failure, the ultimate shear strength is possible to calculate from the ultimate load F_u. The equation is:

$$f_{Cv} = \frac{F_u}{2Be} \tag{5.3}$$

Shear modulus G_c can be calculated by using the equation:

$$G_c = \frac{\Delta FL}{6A_c\Delta w_s} \tag{5.4}$$

where Δw_s is shear deflection:

$$\Delta w_s = \Delta w - \Delta w_b \tag{5.5}$$

In equation 5.5 Δw_B is the bending deflection and Δw is the measured displacement in the middle of the span. The bending deflection can be calculated with the equation:

$$\Delta w_B = \frac{\Delta F L^3}{56{,}34 B_s} \tag{5.6}$$

B_s is flexural rigidity in the equation 5.6 and it can be calculated as follows:

$$B_s = \frac{E_{F1} A_{F1} E_{F2} A_{F2}}{E_{F1} A_{F1} + E_{F2} A_{F2}} e^2 \tag{5.7}$$

Other quantities in the equations: E_{F1} is the modulus of elasticity of the top face, E_{F2} is the modulus of elasticity of the bottom face, A_{F1} is the area of the cross-section of the top face and A_{F2} is for the bottom face, Δw is the deflection at the middle of the span correlated to load increment ΔF (Only the linear correlation is usable), L is the span of the test specimen and A_c is the area of the core's cross-section (EN 14509:2013)

The beam test was originally designed for sandwich panels with thin foam cores. However, the insulation requirements have made sandwich panels thicker and thicker and the ultimate load which is needed for shear failure has also increased. This has led to a situation where crushing failure happens before shear failure. An alternative test method is needed for thick sandwich panels.

The beam test method is described a little bit differently in the European recommendations for sandwich panels by ECCS. This method is recommended if full-scale tests are not possible to arrange. The test is quite similar to the A.3 beam loading test and it is shown on Figure 28.

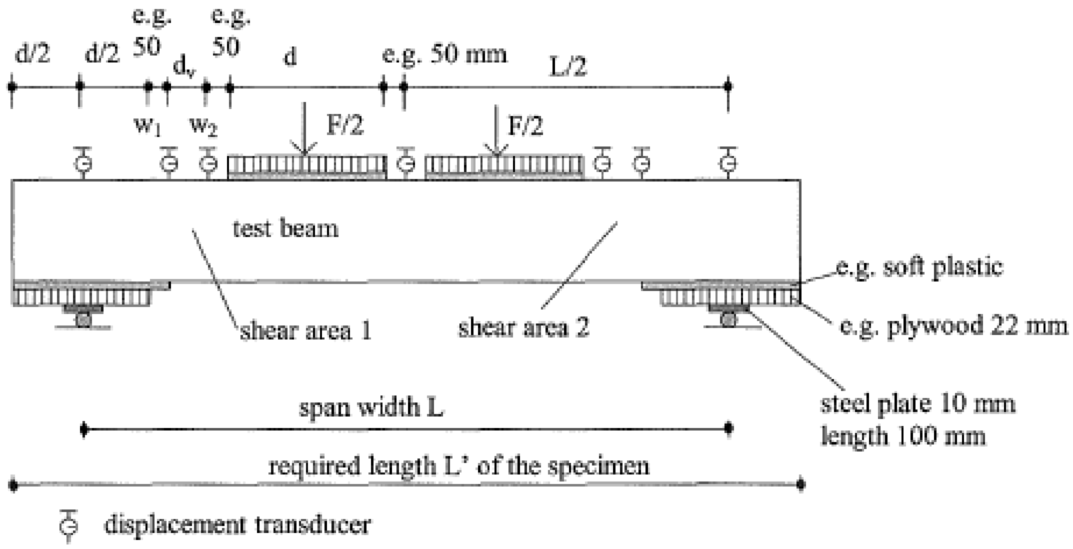


Figure 28: *The beam shear test (European Recommendations for Sandwich Panels 2000)*

This beam test differs from the A.3 beam test in which the loading test is done by using spreading plates. Instead of the steel plates, load is divided onto the test specimen by using thicker plates made i.e. from plywood and soft plastic plates are also used on or under them. The length of the platens and the test specimen should chosen so that crushing failure does not happen.

By choosing the right dimensions for d and L, two shear areas appear in the test specimen between support platens and loading platens. The working length of shear area is 200 mm. The width of the specimen should be about the same as the height of the beam. The recommended loading time, when failure should occur, is between 5 and 10 minutes.

Shear stress in the core can be calculated with the equation 5.3. Shear strain is calculated from displacements w_1 and w_2 with the following equation:

$$\gamma_C = \frac{w_2 - w_1}{d_v} \tag{5.8}$$

where d_v is distance between the displacement transducers. It is possible to calculate the shear modulus when the shear stress and the shear strain are known with the equation:

$$G_C = \frac{\tau_C}{\gamma_C} \tag{5.9}$$

ECCS recommends using full-scale tests when it is possible. The full-scale tests also give more accurate results with discontinuous core materials. In the full-scale tests, it is possible to generate load to the test specimen with air pressure. This simulates wind load more accurately. (European Recommendations for Sandwich Panels 2000)

5.2 Test method for detecting shear strength of mineral wool lamella

The test methods mentioned in previous chapter, do not work with thicker lamellas. This came apparent when testing was done for this thesis. Functional test method for thicker lamellas was needed and in this chapter the design process of it is described.

The width of the test specimen was one assumption for the testing. It was chosen to be 124 mm, which is the width of the mineral wool lamella in the actual product. Other dimensions are determinated experimentally.

All material tests were done with FMT- MEC loading machine and FMT-BEE bending test equipment manufactured by Matertest Oy shown on Figure 29. The nominal range load range of the test machine was from 1 to 25 kilonewtons. All tests were made in with FMT-BEE bending test equipment. It is possible to test beams with 1000 millimeters span with FMT-BEE. (Matertest Oy)

Figure 29: *FMT-MEC material testing machine (Matertest Oy)*

FMT-MEC had its own test program which made it impossible to move the test results from that program to Microsoft Excel. However, all the results and force-displacements curves were printed and the values of the ultimate forces were gathered to Excel.

Only the weakest and strongest mineral wools were selected to be the test specimens. The test arrangements were done with the strongest type of wool. If the arrangement work with it, it was possible to assume that the same method works with the weaker mineral wools. This decision was also made to save time.

The goal of this research was study shear strengths in mineral wool cores. The test specimens are designed so the face sheets or the adhesive do not have any unwanted effect on the test results. The face sheets in all test specimens are flat 0.5 mm steel. 0.5 mm is the thinnest facing sheet used in sandwich panel production in question and it is possible to assume that thicker face sheets work also similarly. 0.5 mm flat face sheet has a minimal effect on the shear strength of the core.

The adhesive used in the test specimens is similar kind of two-component polyurethane glue which is used in the manufacturing of panel. Main difference is that this adhesive does not foam. Foam was not wanted because foaming type of adhesive would have been too fast for practical use when preparing manually the specimens to be tested. To be able to produce all the samples similarly on adhesion point of view would have become too uncertain and difficult. Missing foaming effect was compensated by using rather high coatweight (quantity) of adhesive to secure penetrating of the adhesive properly into the mineral wool core of the specimens

The adhesive used in specimens consists of components named as Loctite UK 8510/Loctite UK 5400 and they are manufactured by Henkel. The mixing ratio by weights was 5 parts of UK 8510 resin and 1 part of UK 5400 hardener and the total amount of adhesive per a face sheet was 480 grams. The mixing of the adhesive was done manually and then spread on the core and a face sheet was placed on it. The bonding was ensured by using steel plates as a weight during hardening time of the adhesion.

All test versions were tested at least with three similar test specimens. Similarity means similar core material and similar dimensions. After each test, failure types were recorded and adjustments to the test arrangement were designed.

Mineral wool lamellas were ordered from the manufacturing process and that ensures dimensions for all test specimens are the same and desired ones. This standardizes the width of the test specimen to 125 mm, and the length to 2400 mm. After cutting the metal face sheets are bonded manually to the core with the technique described earlier.

In all the tests force F and displacement Δw between the support and loading plates were measured. The force is used to calculate stresses and then those stresses were compared with the values given by the mineral wool manufacturer and values available from the quality control of Alajärvi factory. The support stress is calculated by using the equation 4.6, where k is 0. This simplifies the calculation procedures.

The support reaction under load in the middle of the test specimen is calculated with the equation 4.7, where k is 0. These both of these stresses are notable and shall be taken into account. The bending moment and bending stress have an important role and they should be considered in the test results. The bending moment was calculated with the equation 4.1 and the bending stress then with the equation 4.4.

A wrinkling failure might be happen also, but it was decided to leave it out from this analysis because some values in the wrinkling equations are calculated experimentally and the results might not be accurate. The shear failure was the only failure type that is wanted here. The dimensions of the test specimen and test arrangements are chosen so that there would not be other kinds of failures.

The wanted parameters were shear strength and shear modulus. The equation 4.5 was used for shear stress calculation. The shear strength of the test specimen was calculated with the ultimate force and dimensions of the test specimen.

This shear strength includes also the effect of the face sheets. The goal of this thesis is to determinate the shear strength of mineral wool lamella only. Friction-free end connections are tested because of that. Theoretically, in the friction-free end connection, only the face sheets works as a strength giving structure. Friction-free connections are described later.

A mineral wool lamella with face sheets is called a beam later on in the results and equations. The mineral wool lamella is only the mineral wool core without the face sheets. The shear strength of mineral wool lamella is estimated by using the equation 5.10:

$$\tau_{lamella} = \tau_{beam} - \tau_{average\ of\ face\ sheets'part} \tag{5.10}$$

where τ_{beam} is the shear strength of the whole test specimen. $\tau_{average\ of\ face\ sheets'part}$ is the average shear strength from the non-friction end connection test. It was assumed that only the face sheets impacted on shear strength in the non-friction tests. The shear strength of the lamella is calculated from the shear strength of the beam by reducing the face sheets’ part from the shear strength. It is possible to estimate their average effect from the results of the friction-free end joint connections.

The displacement of the test beam is measured in the middle of the span in EN 14509:2013. FMT-MEC measures the displacement of the moving beam in the middle of the apparatus. This works on the compression or tensile tests because displacement is measured from the same line which goes through of the center of the test specimen. This is shown on Figure 30.

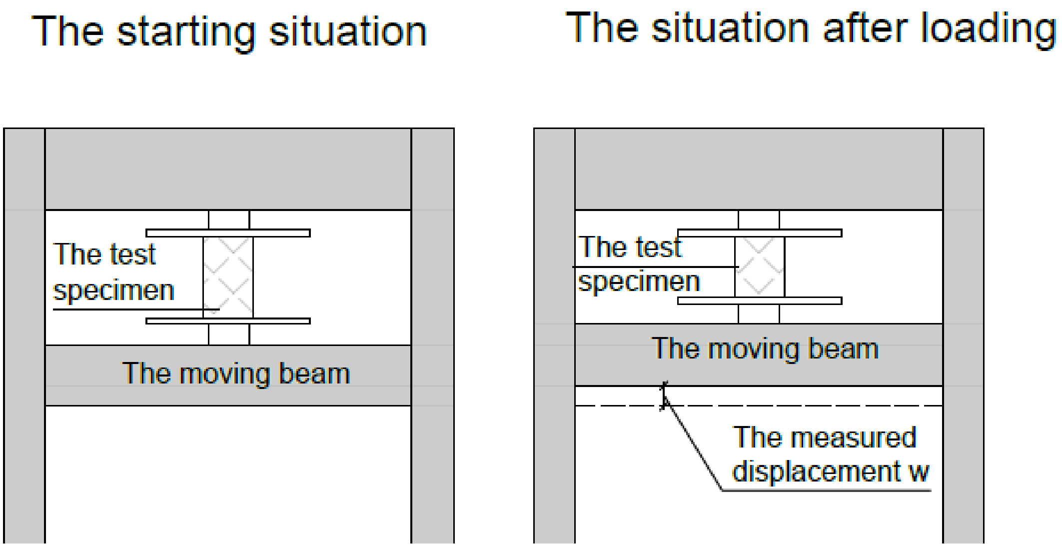


Figure 30: *The displacement measuring in the compression test*

The beam test requires FMT-BEE bending equipment, which is shown on Figure 31. With FMT-BEE bending equipment beam displacement is measured between load and support plates, shown on Figure 32. The exact value of the shear modulus is challenging to calculate without the exact displacement of the whole span.

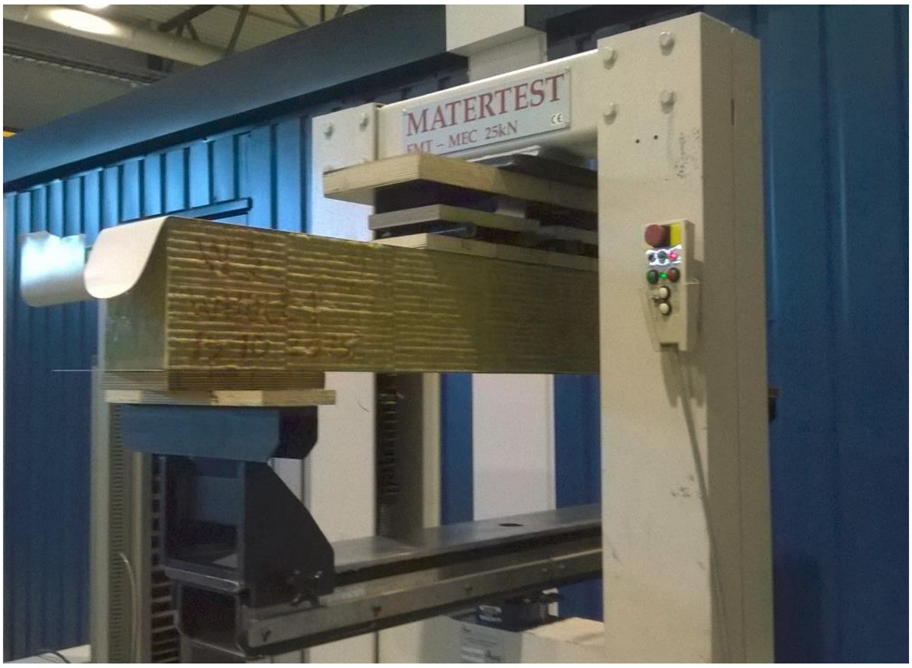


Figure 31: *FMT-BEE bending test equipment*

It is still possible to calculate the shear modulus because the displacement and the force are measured. However the displacement values are not from the middle of the span and calculated shear modulus is relative.

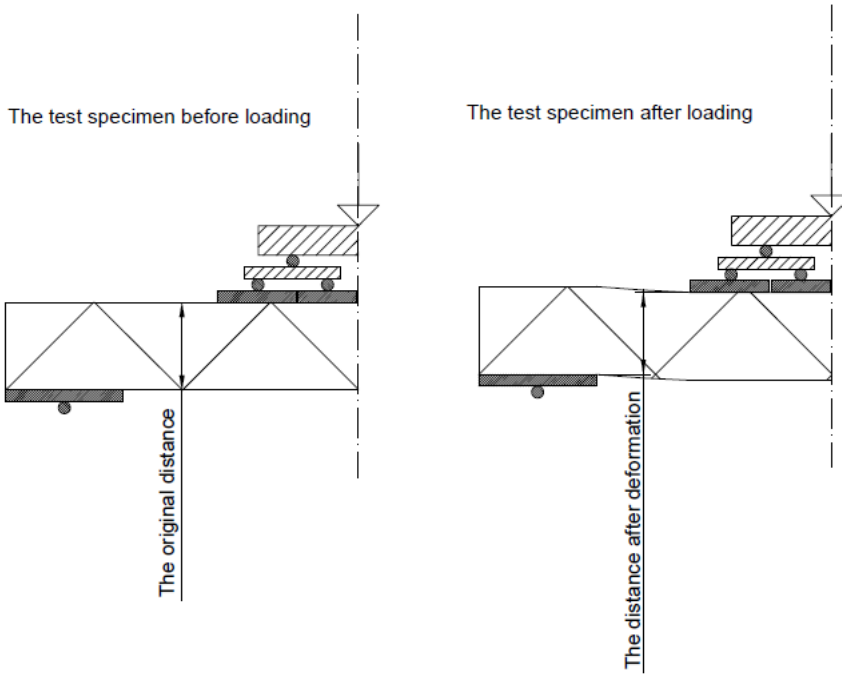


__Figure 32:__ The measured displacement in the FMT-BEE test apparatus

The shear moduli were calculated from the straight part of the force-displacement curve. Usually the curve was straight between the 20-70 percent of the ultimate force and then the displacement was 20-70 percent of the total displacement. The values of used force were selected from this area and corresponding values of the displacement were also picked up. 20-70 percent areas are shown on Figure 33.

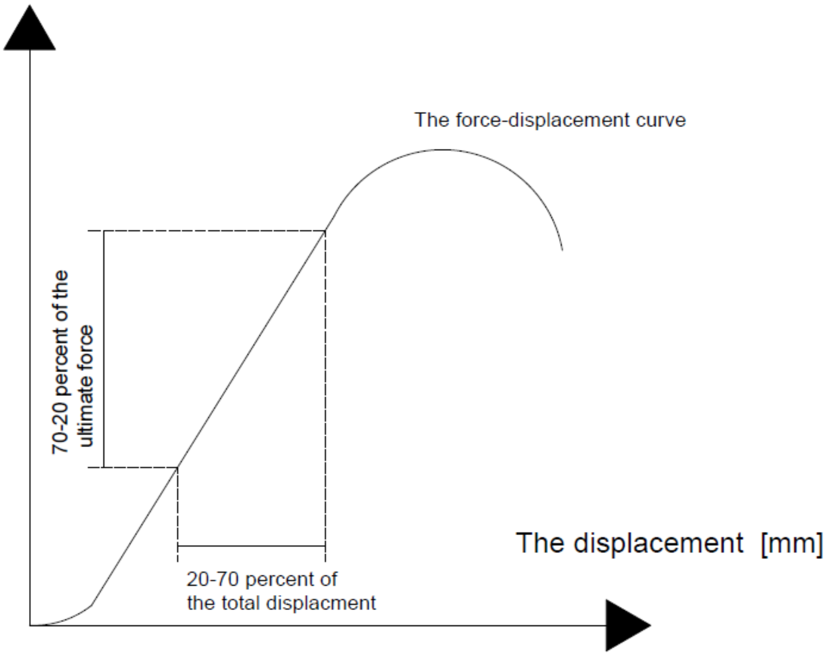


__Figure 33:__ The force-displacement curve

Shear moduli of the test specimens are comparative with each other because displacement is measured at the same point with every test specimen. Shear strength is the primary study topic and the shear modulus is used to see difference in the stiffness between different end connection types.

The search for the test arrangement started with EN 14509 beam test method. The first version is on Figure 34. The first test version contained two 100 mm wide support plates in both ends of the test specimen and two 150 mm long load plates. This test method worked somehow with weaker mineral wools, however with thicker and stronger cores, compressive or wrinkling failure happens before shear failure.

The numeric values of compression stress under load plates and on the support plate were calculated. Shear stress was also calculated and dimensions were changed to change the ratio of different strengths in the test specimen.

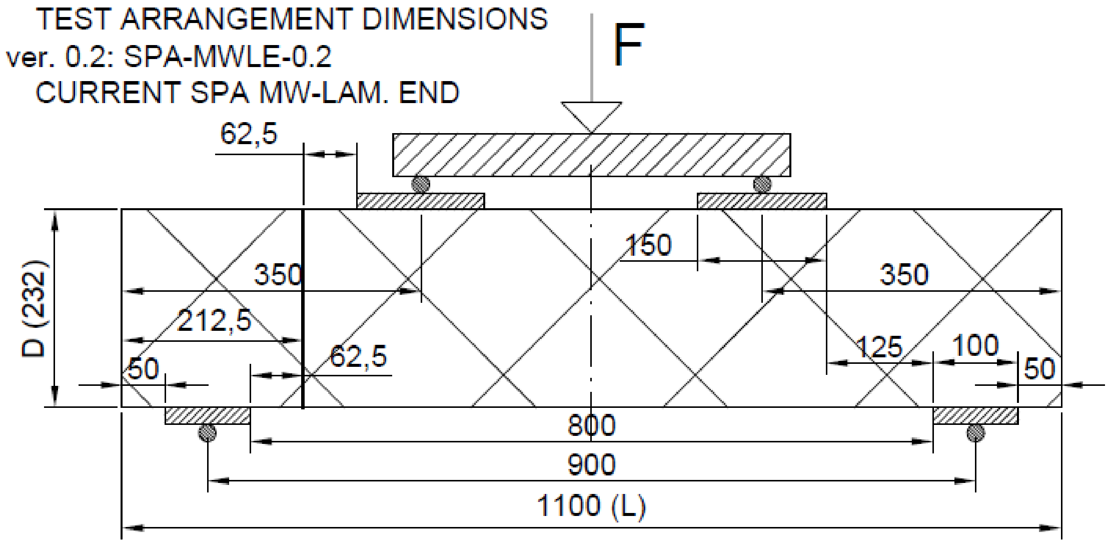


Figure 34: Test version v.1

The thickness of test specimens was 232 mm at the first test version. 232 mm is the thickest used dimension in the sandwich panel production and the goal was for the test method to present this as well as possible. 232 mm didn’t work with FMT-MEC test machine, because the span is limited to 1000 mm. Shorter span limited the size of the support and the load plates and this affect on the compression.

The ratio between shear and compression stress was 1:1,2 with strongest tested stone wool when the span was 1000 mm and the thickness of the test specimen 232 mm. The compression failure happened before shear failure and test method did not work as planned.

In the all test versions, the support plates were made from 15 mm thick plywood and steel rolls were used to divide and carry the force uniformly to the load area. The test specimens were loaded with speed specified in EN 14509. It recommends to choosing the uniform loading rate, so the failure happens from 1 to 5 minutes after starting the test. The same loading rate is used in every actual test during this research.

During the first tests, failures happened under the load plates or on the support. Shear strength was so high compared to the compression, that shear failure did not happen. In the firsts test arrangement specimens failed by wrinkling near the load area, shown on Figure 35 or by crushing failure on the support, shown on Figure 36.

Figure 35: *Wrinkling failure next to the load plate*

The support and load plates can rotate freely in all the test versions. If the upper face sheet of the test specimen even slightly uneven, that part is vulnerable to wrinkling with higher loads.

Figure 36: *Crushing failure on the support with the thicker test specimen*

The test version v.1.x was also tested with the glass wool test specimens. Strength characteristics of the glass wool core in question are significantly lower in comparison with the stone wool core, which were used in the tests. The glass wool test specimens with the similar dimensions than the mineral wool test specimens failed by shear. This proved the functionality and suitability of the test method.

In test version 2, the support plates were wider with the width of 150 mm. The force *F* was divided onto the test specimen by using four load plates instead of two. Otherwise, the dimensions of the test specimens remained the same as in version 1. Test version 2 is shown on Figure 37.

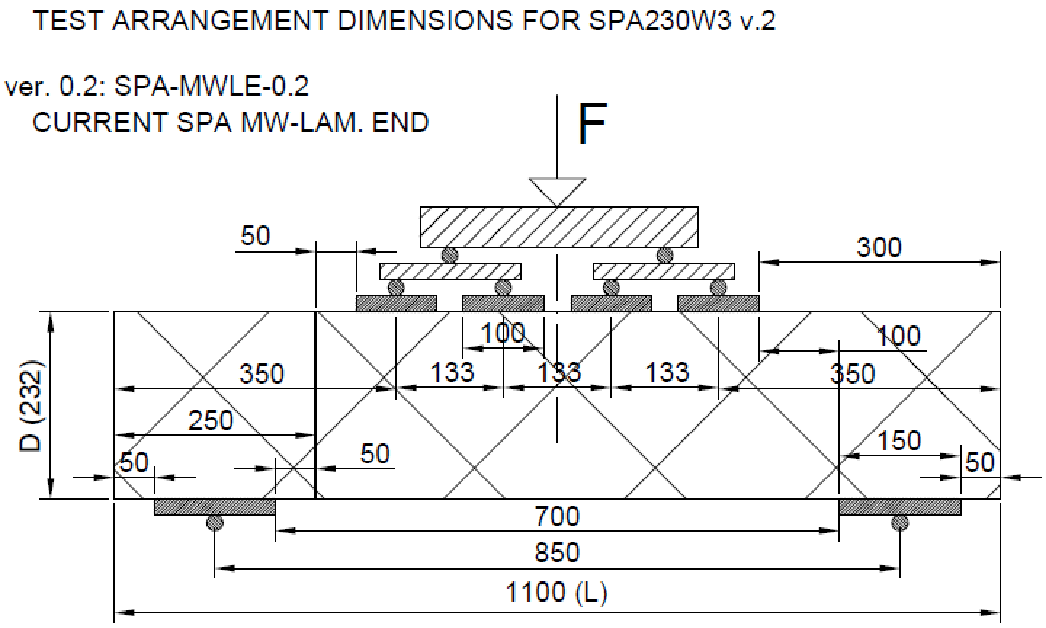


Figure 37: *Test version v.2*

The same problems appeared with version 2 which appeared in the first one too. The compression strength of the test specimen was too high compared with the shear strength and only wrinkling and crushing failures popped up. Wrinkling failure was more common than crushing on the support.

In the next version, the sizes of the load and support plates were increased. Otherwise version 3 remained the same than version 2. This version is shown on Figure 38

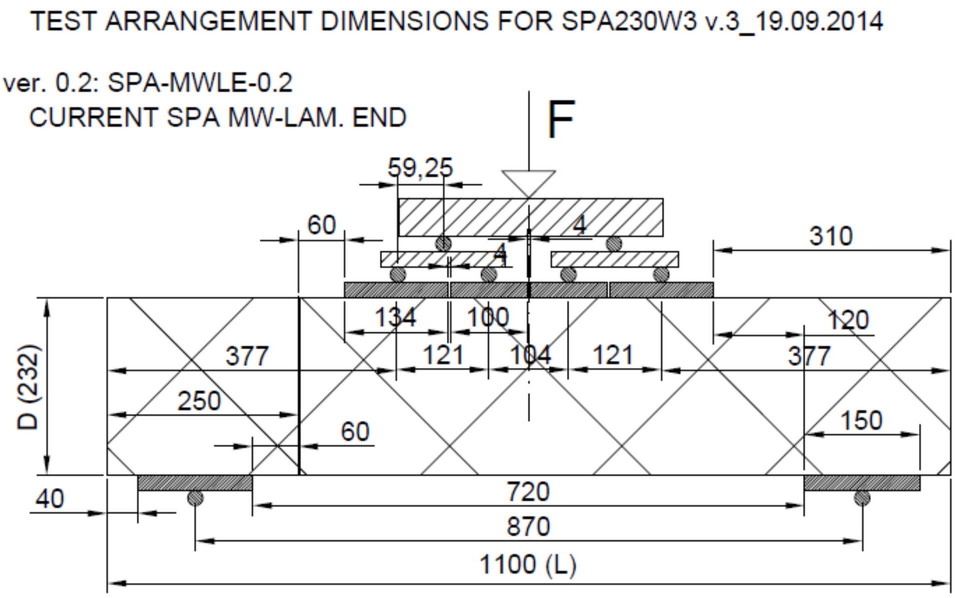


Figure 38: *test version v.3*

Version 3 did not ensure shear failure. Before the design of the next version, all the changeable test parameters were listed because every test event consumed time and disturbed normal testing. After listing, the parameters were ranked and next test versions were designed by concentrating only on the major parameters. All these parameters are listed below on Table 3.

Table 3: *Parameters of test method*

Parameters of the test arrangement and test specimens	
Major and changeable parameters	**Minor and not-changeable parameters**
Thickness of the test specimen	Span (maximum 1000 mm)
Size of the load area	Width of test specimens (125 mm)
Size of the support area	Type of materials
Distance between load and support plates (so called shear area)	

The most of the parameters were connected to each other and changing one made limitations to others. For example, the length of the span influenced boundaries to the support and load areas and reduced or increased the distance between the support and load plates.

The maximum span was 1000 mm because of test machinery. ECCS recommends that the distance between the support and load plate should be equal or bigger than the thickness of lamella. The strongest tested mineral wool required wide support and load plates, and in the final version, the major design parameter was thickness of the test specimen.

The span also limited the length of the plates. From version v.4.x onwards the load area consisted of two 134 mm long and two 100 mm long plywood plates and on the supports were 200 mm long plywood plates. The dimensions were chosen to minimize compression stresses on the supports and under the load beam. The length of the shear area was also maximized.

The thickness was first reduced to 200 mm in the test version v.4.x and then again to 150 mm in the version v.6.x to raise shear stress in comparison with other stresses. 150 mm thickness is still enough to study different lamella connections. The final version is shown on Figure 39.

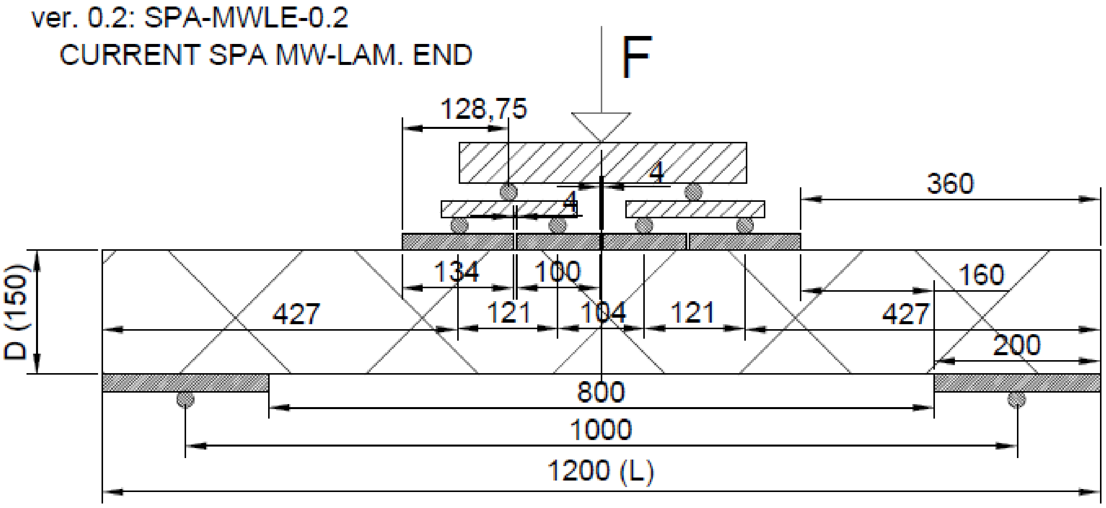


Figure 39: *Final test version v.6.2*

Earlier versions were tested with three test specimens each. Data was collected to approximately calculate the stresses at the failure point. With the ultimate force F_u shear stress, compression stresses and bending stress were calculated and these values were compared with declared values given by the mineral wool manufacturer.

This was the way see how the dimension changes in the test version affected the results and failure types. Compression failures were the most common failures in the earlier versions with thicker lamellas. When the size of the load plates increased and thickness remained the same, the failure type changed to wrinkling.

Final version v.6.2 was tested properly with five test specimens after final design and harsh tests. This amount was chosen to ensure shear failure appearing and see how much the ultimate force varies. Five test specimens were made from the strongest type of mineral wool. Typical shear failure appeared between the load area and the support, typical failure is shown on Figure 40.

Figure 40: *Test specimen with shear failure*

Shear failure did not appear suddenly during the progression of the test. After reaching the shear strength, the test specimen started to fail slowly. The structure of mineral wool prevented the formation of impulsive cracks. Shear failure was possible to see first from the load-displacement curve of the test machine and then a little bit later from the test specimen.

The results from the test method design phase can be found on appendix B. One goal of the design phase was discovering the test specimen which resembled closely whole sandwich panel. 125 mm is the same width as used in lamellas in the production. The test apparatus limited the length of the lamella to 1200 mm but this is still enough to do tests on mineral wool lamella end joint connections.

Changes made from test version to other:

- **v.1.x → v.2.x**
    - the amount of the load point increased to four
    - the size of support plates was increased from 100 mm to 150 mm
- **v.2.x → v.3.x**
    - the size of outer load plates was increased from 100 mm to 134 mm
- **v.3.x → v.4.x**
    - The thickness of test specimen was decreased from 232 mm to 200mm

    - the length of the test specimen was increased from 1100 mm to 1200 mm
- **v.4.x → v.5.x**
    - the size of support plates was increased from 150 mm to 200 mm
    - the length of the test specimen was increased from 1200 mm to 1340 mm
- **v.5.x → v.6.x**
    - The thickness of the test specimen was decreased from 200 mm to 150mm
    - the length of the test specimen was decreased from 1340 mm to 1200 mm

5.3 Mineral wool lamella's end joint testing

Developing a functional test method design was the first part and the goal of this research. Test version v.6.2 worked also with the strongest mineral wool type. All end connection tests are made with this version.

Second part consisted of reference testing and actual end connection testing. The reference test was used to get the basis for the comparison of different end connections.

All the test specimens for the reference series and end connection series were made from the same mineral wool batch. Two different mineral wool grades were used. Chosen grades were the strongest stone wool used in the panel production and glass wool which is used in the production. Stone wool was the main core material and glass wool was used to see how the weaker mineral wool works with end connections similar to harder stone wool.

The compression and tensile strength of mineral wool batches were also tested. With them it was possible to compare tested strengths with values given by the wool manufacturers. Relation between the actual compression and the shear strength was also possible to determine.

All the tests were done with the same test machine and in the same place. All the test specimens were made in a similar way and the same adhesive and face sheets were used. Testing was done at the same time as normal quality testing.

Preparation of one test specimen took approximately half an hour and an average testing time per one specimen was 15 minutes. The test machinery was used by daily quality control and this created a challenge to create a working testing time plan.

Preparation of the test specimens and their testing were scheduled to happen mainly on exact days. Then during one day all the samples for the next test session were made.

This was a more time efficient way to do testing, because test machinery had to be adjusted for beam testing.

The goal was to test all the similar test specimens, with similar end connections, during the same tests session to eliminate all unwanted anomalies. Possible anomalies could come from the set-up of the test machinery or the loading plates and the steel rolls.

5.3.1 The reference series

The reference series included the test with full lamellas, lamellas with similar end connections that are used in production and lamellas with friction-free end connection.

ECCS recommends using at least three tests per property. Especially, the properties of mineral wool can vary and the purpose of the three tests was to check that average value from test remains between the known material properties of the tested mineral wool.

The full lamella test specimen is made from one mineral wool piece. The whole lamella is also the basis for other test specimens. In all end connection tests, the connection is located in the middle of the shear area; this is shown on Figure 41.

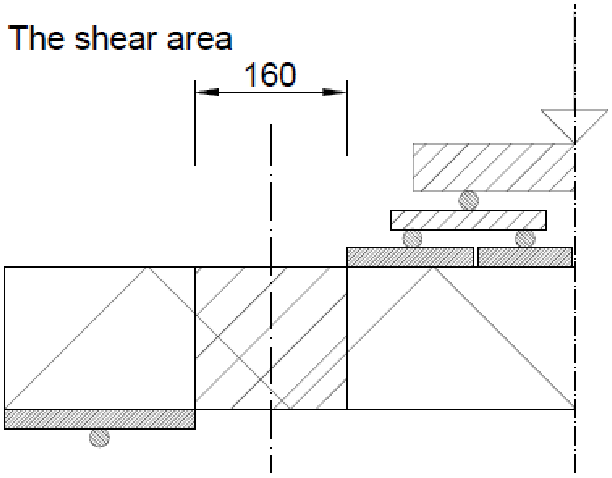


Figure 41: *Shear area of test specimen*

Theoretically shear stress is highest near the edge of the support plate. The end connections were located 80 mm from it to the center of the test specimen to minimize unwanted impacts from the support.

The reference series contained three types of specimens. The first was the test specimen with full lamella between the face sheets. This type was assumed to have the highest shear strength.

The second was similar end connection type that is used in manufacturing at the moment. The straight ends of lamellas are placed next to each other and friction can affect the connection under load. The connection was made by cutting the lamella of the test specimen before the face sheet was added. During the spreading of the adhesive, pieces of the lamella were pushed gently to close each other. This ensures that the connection is tight enough and that friction has a role to play.

The third connection type was the full friction connection. It was made with the mineral wool knife to the lamella after the face sheets adding. The lamella was cut with straight line from the shear area and the face sheets prevented any movements, so the pieces of the lamella stayed close to each other and there was pressure between the surfaces.

The fourth connection type in the reference series was the friction-free connection. The purpse of using of this type of connection was to study the face sheets' part of the total shear strength. In the test specimens, mineral wool lamellas were cut in the middle of the shear area before adding the face sheets. A plan paper was placed between the lamellas to prevent the fibres of mineral wool from touching the fibres of the other lamella.

This minimizes the effect of friction and mineral wool lamellas started to slide when the shear strength of the face sheets was reached. The face sheets were assumed to behave similarly in other tests and have a fairly similar same effect on the shear strength of the whole test specimen. The number of tested test specimens was listed below on Table 4.

Table 4: *The test specimens in the reference series*

Connection type \ mineral wool type	**Stone wool**	**Glass wool**
Full lamella	8 pieces	3 pieces
Connection used in manufacturing	4 pieces	Not tested
Full-friction connection	5 pieces	3 pieces
Friction-free connection	5 pieces	3 pieces

The number of test specimens was decided on the basis of the time limitations and of the accuracy of the results. Stone wool was the main core material and more test specimens were made of it. There were only three specimens made of glass per end connection type and their function was to show the difference between the hardest and weakest mineral wool type.

5.3.2 The end connection series

In this research actual end connections can be divided into two categories: mechanical connections and chemical connections. Mechanical connections include different milled notches at the end of the lamella and other mechanical connectors such as metal plates. Chemical connections include all different glue connections.

In this research mechanical end connections were made by using water cutting. This made it possible to test very sharp shapes. In the production, it is impossible to achieve sharp shapes because milling technique has its limitations how sharp edges it can make.

The cut was made to 2400 mm long lamella. During the cutting, mineral wool absorbed water and test specimens were let to dry at least one week after cutting. Then test specimens were prepared like the test specimens in the references series. Some tested shapes are shown on Figure 42.

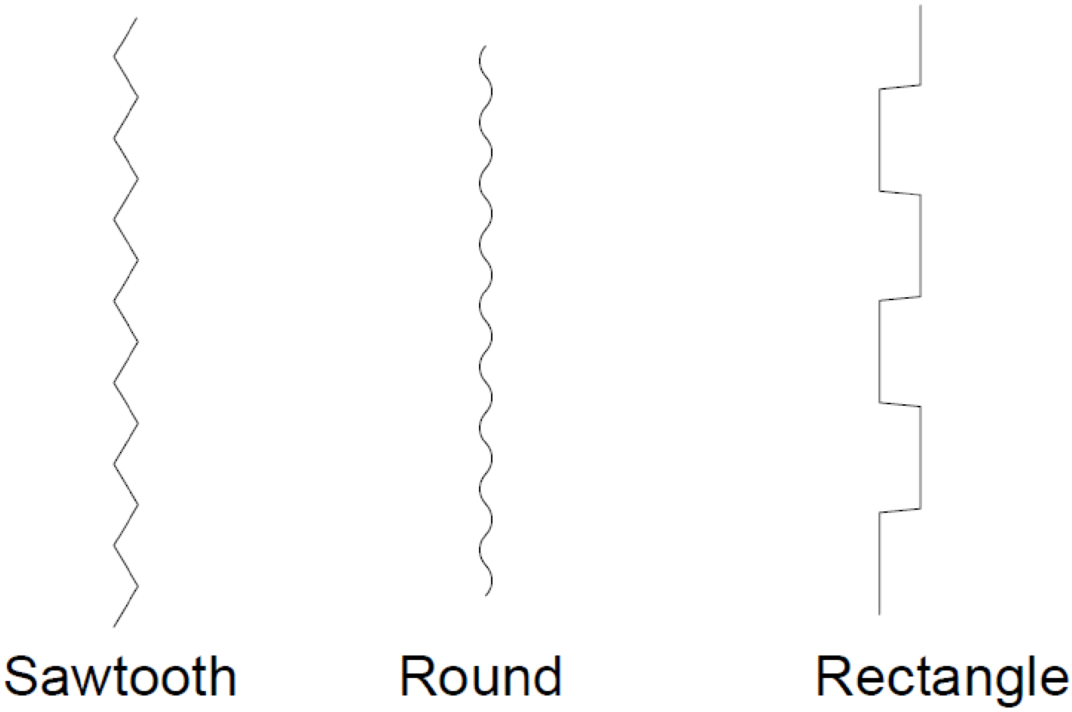


Figure 42: *Used shape types*

A total of six different notch types were tested; three types of sawtooth notches, two types of round notches and one type of rectangle notch. The depth and height of notches varied between different types. The main focus was on shapes that can be used in the production and mainly this means round notches. All details and dimensions of tested notches are described in Appendix B.

Another tested mechanical connection type was the plate connection, in which the mineral wool lamellas were connected to each other by using a metal plate. The plates were 50 mm wide, 0.5 mm thick and 100 mm long and they were placed in the middle of the lamella and pushed inside of the lamella. Only one size metal plate was tested because this connection type is challenging to adapt to the manufacturing process. All tested mechanical end connection types are listed below on Table 5.

Table 5: *The test specimens in the mechanical end connection series*

Connection type \ mineral wool type	Stone wool	Glass wool
Sawtooth type 1	6 pieces	not tested
Sawtooth type 2	3 pieces	not tested
Sawtooth type 3	3 pieces	3 pieces
Rectangle type 1	6 pieces	3 pieces
Round type 1	3 pieces	not tested
Round type 2	6 pieces	3 pieces
Metal plate	3 pieces	not tested

The bigger the number of the sawtooth type, the bigger was the size of the notch in the end connection. In the round end connection types, the number indicates the size of the notch.

Chemical connections included all the hot-melted and two-component polyurethane glue connections. Glue connections were separated into different types by the used glue, the amount of glue and the area of glued surface. Three different sizes of areas were used and they covered 33%, 50% or 100 % of total area of the end surface. The area of the end surface was the same in every lamella and the height of the end area was 150 mm and width 125 mm.

Hot-melt glue was left out from the actual end connections after the first tests with it. The reason was the amount of glue it required. The hot-melt glue that was used did not foam at all and because of that, it did not create a good connection between the lamellas unless the amount of used glue was big enough.

Two-component polyurethane glue contained Loctite UK 8573 B3 as component A and Loctite UK 5400 as component B. The final mix contained five parts of component A and one part of component B by the weight-ratio. This polyurethane glue was chosen because it foams and it has a long pot life (110-150 second). Foaming effect secures that adhesion penetrates properly into a mineral wool core The long pot life and open time helped preparing the test specimen. The glue amounts varied from 2kg per square meter to 0.5 kg per square meter.

Glue connections were also placed in the middle of the shear area. The lamella was first cut to two pieces by using the band sawing machine. The cutting point was the same as the glue connection point. The band sawing machine ensured that the end of the lamella is straight.

Glue was spread on the smaller piece of the lamella after the cutting. The glued area was the rectangle centered in the middle of the surface of the lamella, shown on Figure

43. The glued areas were measured and marked on the surface and they went from one side to the other.

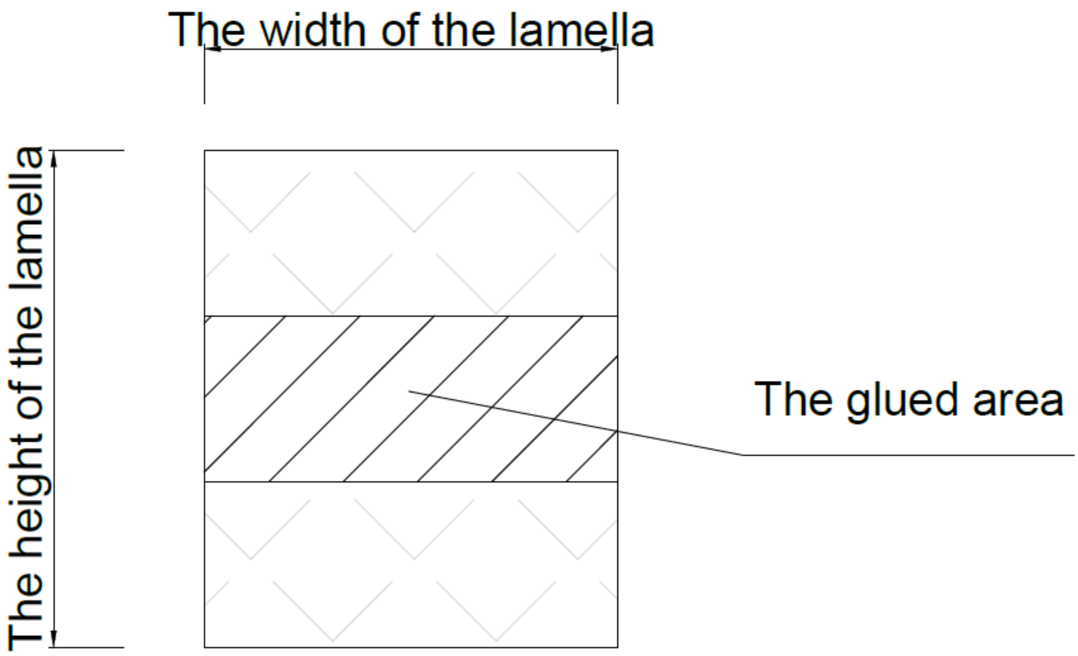


Figure 43: *The glue area in the end of the lamella*

The amount of glue was measured and then the bigger piece of the lamella was placed next to the smaller piece. The ends of the piece were gently pushed together but no additional pressure was used. Additional pressure was left out because this simulated the manufacturing process better. The detailed information about the glue connections is presented on Appendix B. The tested specimens of glue connections are listed below on Table 6. The numbers showing the amount glue used indicate how much glue was used in the connection. The bigger the number, the less glue was used.

Table 6: *The test specimens in the glue connection series*

Connection type \ mineral wool type	**Rock wool**	**Glass wool**
33 % glued area, the glue amount 1	3 pieces	not tested
33 % glued area, the glue amount 2	3 pieces	3 pieces
33 % glued area, the glue amount 3	3 pieces	not tested
50 % glued area, the glue amount 1	3 pieces	not tested
50 % glued area, the glue amount 2	3 pieces	3 pieces
50 % glued area, the glue amount 3	3 pieces	not tested
100 % glued area, the glue amount 1	not tested	3 pieces
100 % glued area, the glue amount 2	3 pieces	not tested

5.3.3 The three lamellas test series

The test apparatus did not limit the width of the test specimen to 125 mm and it was possible to test wider test specimens as well. The test specimen with three lamellas was designed to simulate the full-scale sandwich panels better than the specimen with only one lamella. The three lamella test specimens were tested with the test version v.6.2. The other dimensions of the used test method remained the same, only the total width of the test specimen was increased from 125 mm to 375 mm. The three lamella test specimen is shown on Figure 44.

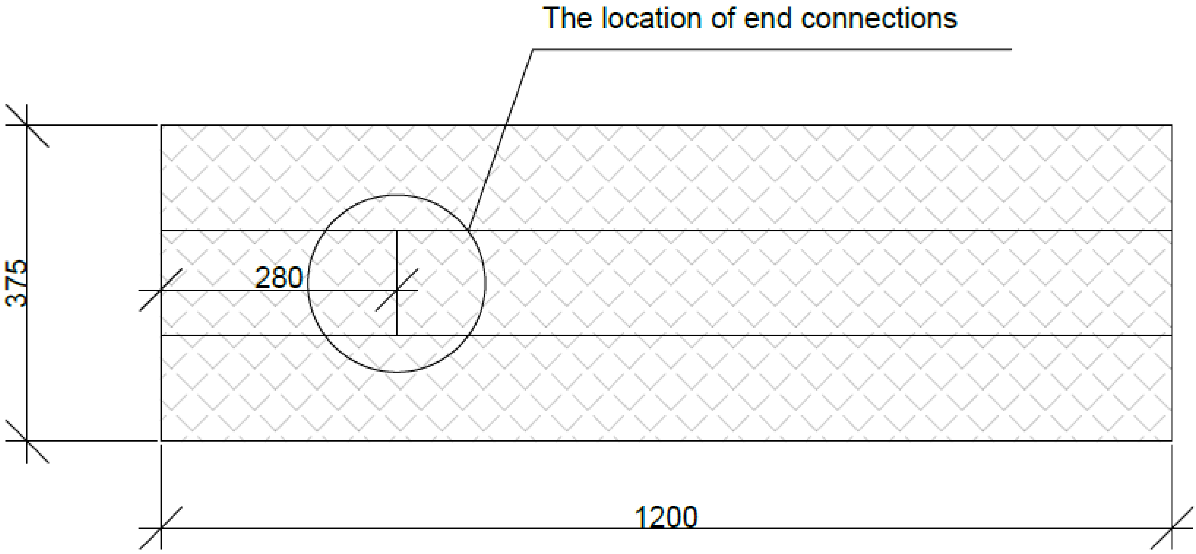


Figure 44: *The three lamellas test specimen*

The three lamella test specimens had the same materials in the core and the same the face sheets as the one lamella test specimens. There were some minor differences during the preparation of the test specimens. The adhesive was spread on the face sheet and mineral wool lamellas were placed on it. The amount of adhesive was a little bit smaller than with the one lamella test specimen. The total amount of two-component glue per the face sheet was 720 grams.

End connections were placed in the centermost lamella. The location was 280 mm from the end of the lamella. The middle lamella was chosen because other two lamellas support it symmetrically and unwanted rotation was avoided this way.

This test series was tested after the actual end connection tests. One lamella test specimens were the main subject of this research and only a few three lamellas test specimens were tested. End connection types of the three lamellas series were chosen according to the earlier test results with the one lamella test specimens. The mechanical connection type round 2 and glue connection with 50 % glue area were chosen to test because they were the most executable options to be used in manufacturing. Only stone wool lamellas were tested because of the lack of test time. Tested specimens are listed below on Table 7.

Table 7 : *The three lamellas test specimen series*

Connection type \ mineral wool type	**Stone wool**	**Glass wool**
Full lamella	3 pieces	not tested
Round type 2	3 pieces	not tested
glue connection with 50 % glue area	3 pieces	not tested
Connection used in manufacturing	1 piece	not tested

In all of the tests, the results were gathered from the program of FMT-MEC and then placed in Excel. The test results are shown on Appendix C. The force-displacement curves were recorded and relative shear moduli were drawn from the results. The shear moduli were relative because test machinery could not measure the displacement of the middle of the span.

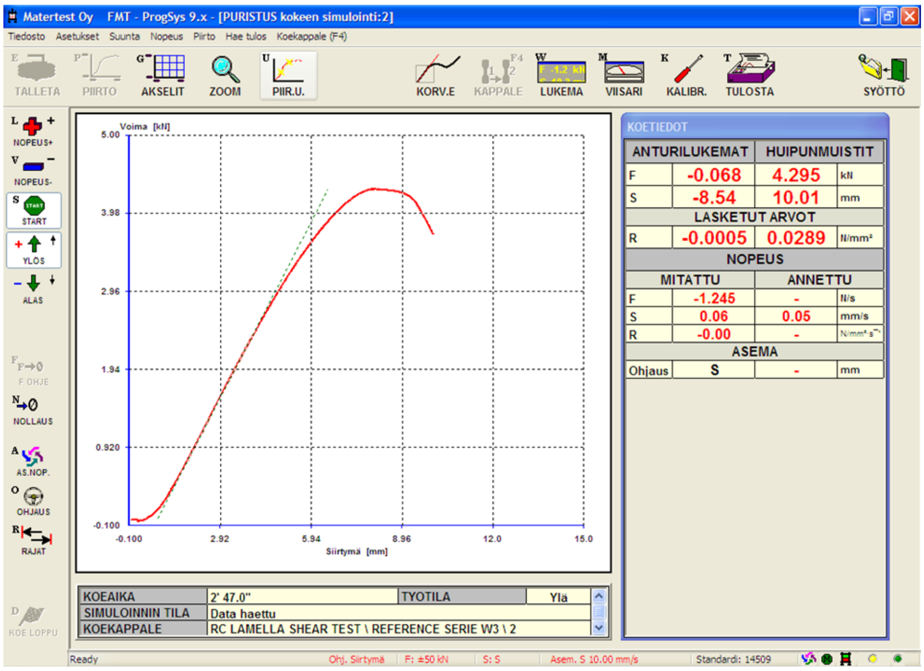
Because the displacement was measured from the same point with every test specimen, it was possible to compare the stiffness of the test specimens. The displacement was measured between the support and load plate and it was used in a force-displacement curve.

6. TEST RESULTS AND CONCLUSIONS

6.1 Test method

A.3 and A.4 in sandwich panel standard EN 14509 gave a good basis for the search of the best test method. The original goal was to find a method with which with one lamella simulates full-scale sandwich panels as well as possible. Another goal was to find a method, which works with the thickest sandwich lamellas. However during the testing and designing process, limitations of the test apparatus were became apparent and this limited the thickness of the stone wool test specimens to 150 mm. The test apparatus also limited the span of the test specimen to 1000 mm.

FMT-BEE gave the force-displacement curve from every test. It was not possible to move the results straight to Excel. The values were gathered manually. Figure 45 shows one example of the force-displacement curve.



ANTURILUKEMAT		HUIPUNMUISTIT	
F	-0.068	4.295	kN
S	-8.54	10.01	mm
LASKETUT ARVOT			
R	-0.0005	0.0289	N/mm²
NOPEUS			
MITATTU		ANNETTU	
F	-1.245	-	N/s
S	0.06	0.05	mm/s
R	-0.00	-	N/mm²·s⁻¹
ASEMA			
Ohjaus	S	-	mm

KOEAIKA	2' 47.0"	TYOTILA	Ylä
SIMULOINNIN TILA	Data haettu		
KOEKAPPALE	RC LAMELLA SHEAR TEST \ REFERENCE SERIE W3 \ 2		

Ready Ohj. Siirtymä F: ±50 kN S: S Asem. S 10.00 mm/s Standardi: 14509

__Figure 45:__ The example of the test results from FMT-BEE

With different test apparatus, it might be possible to test strong stone wool test specimens, which are thicker than 150 mm. A longer span is needed for the support and load areas to be longer.

However, with glass wool it would have been possible to use thicker specimens because the glass wool cores are weaker. 150 mm thickness was chosen to be used in all the test specimens so that it was possible to compare both mineral wool type results with each other. The test method searching phase revealed that 150 mm is enough to see the difference between different end connection types.

6.1.1 Notable things about the test specimens

The goal of this thesis was to find the method for the shear strength testing of mineral wool lamellas. These lamellas simulated full-scale sandwich panels as well as possible but there were some things which made the test specimens to differ from the actual product.

The production of test specimens was the major difference. All the test specimens were made manually. This affected the gluing process. The amount and type of glue used with the test specimens were different to the glue used in manufacturing. The glue of the test specimens did not foam and it was spread on mineral wool instead of the face sheet. That way, a good connection between the core and the face sheets was ensured.

The amount of used glue was significantly bigger with the test specimens. This was the second way to ensure a working connection. After the spreading of the glue, some pressure was needed. With the test specimens, it was done by using weight plates. The pressure was smaller than in the manufacturing but with the weight plates, amount of it was easy to keep the same with every specimen.

The bigger amount of glue formed a 2-4 mm thick mixture layer onto the test specimens. The layer contained the mixture of glue and wool and it appeared under the face sheets. This layer might have had a small impact on the total shear strength of the beam but its effect was possible to approximate from the friction-free end connection tests. With the friction-free test specimens, it was possible to assume that only the face sheets and this layer of glue and wool had an effect on the shear strength. In the results of the lamellas, this effect was removed by using the equation 5.10.

The preparation of the end connection was something that had an effect on the shear strength. This was noticed with both, mechanical and chemical connections.

The shear strength would be reduced if the ends of lamellas were not tightly connected to each other. In a mechanical connection, the space between lamellas reduced the effect of friction because there were fewer surfaces which touched each other. This enabled the bending forces and bending displacement to affect the connection more. One example of the gap is shown on Figure 46.

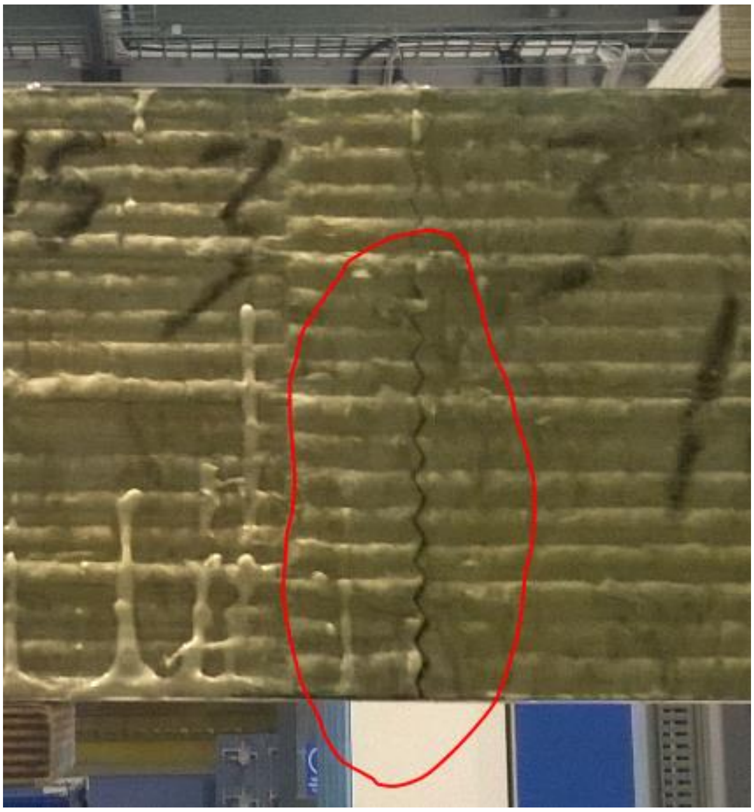


Figure 46: *The gap in the mechanical connection*

In the chemical connection, the distance between the lamellas was directly propotional to the strength of the glue connection. Even though,two-component glue used foamed a little bit, the gap reduced the depth of glue penetrating.

Every test specimen was inspected during the test and the test result was abandoned if there were signs of the effect of the reduced strength resulting from the gap between the lamellas.

The three lamellas series revealed that the effect of the end connection was apparent with one lamella test specimens. In the three lamellas tests, two full lamellas support the lamella with the end connection. However, there was still enough difference between the results of the different end connections.

The differences between the end connections were discovered in the one lamella tests. The end connection solutions, which did not work at all in one lamella, were left out from the three lamella tests. Below some major observations about the test specimens are listed.

- The amount of adhesive should be the same in every specimen
- The same preparation method should be used with every specimen
- There should not be a gap between the lamellas in a mechanical end connection

6.2 Different end connections

The actual tests were made by using mineral wool batches, whose tensile and compression strengths were also tested. The strength of mineral wool can vary even between mineral wool slabs from the same batch, but the goal was to minimize the effect of quality variations.

The reference series was done first. The results were used to compare different end connections to the full lamella.

6.2.1 Reference series

The reference series contained four types of test specimens; full lamellas, friction-free connections, connections used in the present production and full friction connections. All these types were tested with stone wool and glass wool, except the connection used in the production. It was tested only with stone wool cores.

The reason for this was the full friction connection, which was thought to present production style end connection as much as possible. However, end connections in the actual product are not so tight so that friction does not affect the full scale product.

The fourth end connection type was developed later than the full lamella, the full friction and friction free end connection to simulate production style end connections better. Lack of time and test materials forced to test it only with stone wool.

The results from the stone wool reference series are shown on Figure 47. The difference between the full lamella and other type is significant. One of the reasons might be the total strength of stone wool. Very tight, full stone wool lamella had high shear strength compared with the lamella where only the face sheets carry forces at the end connection point.

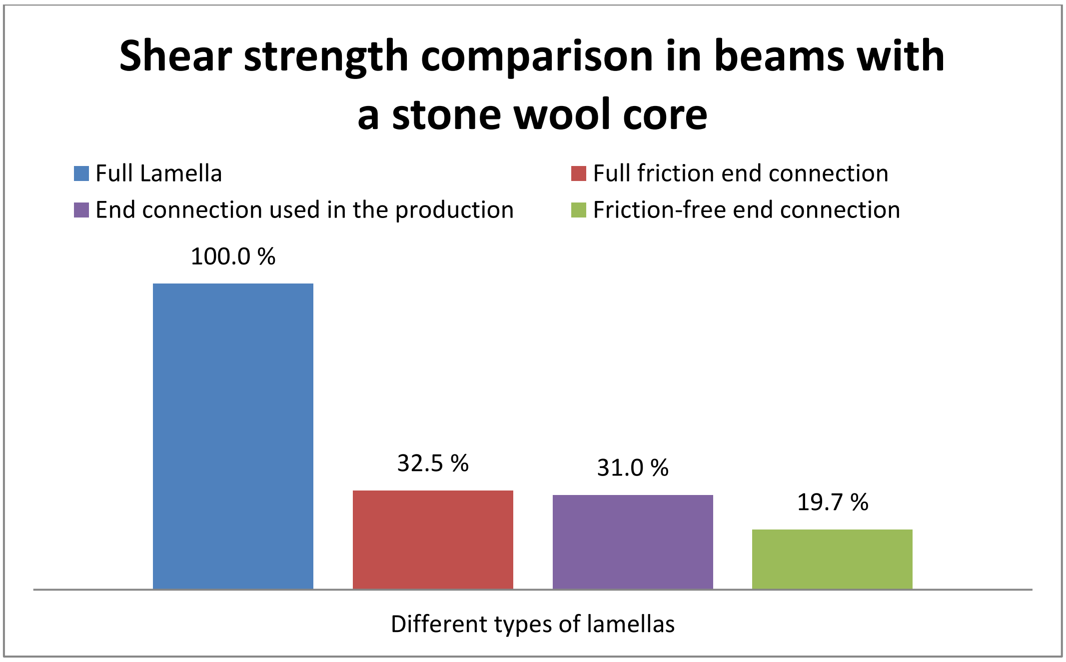


Figure 47: *The results from the stone wool reference series*

Friction had effect on the shear strength, but the difference between the end connection used in the production and the full friction end connection is small. With results from the non-friction end connection test, it was possible to calculate the face sheets' impact on the total shear strength by using the equation 5.10.

In the results of the reference series, the effect of the face sheets was still included. This effect was removed later in the end connection tests. After removing, the result of the tests gave more accurate data about the shear properties of the lamellas.

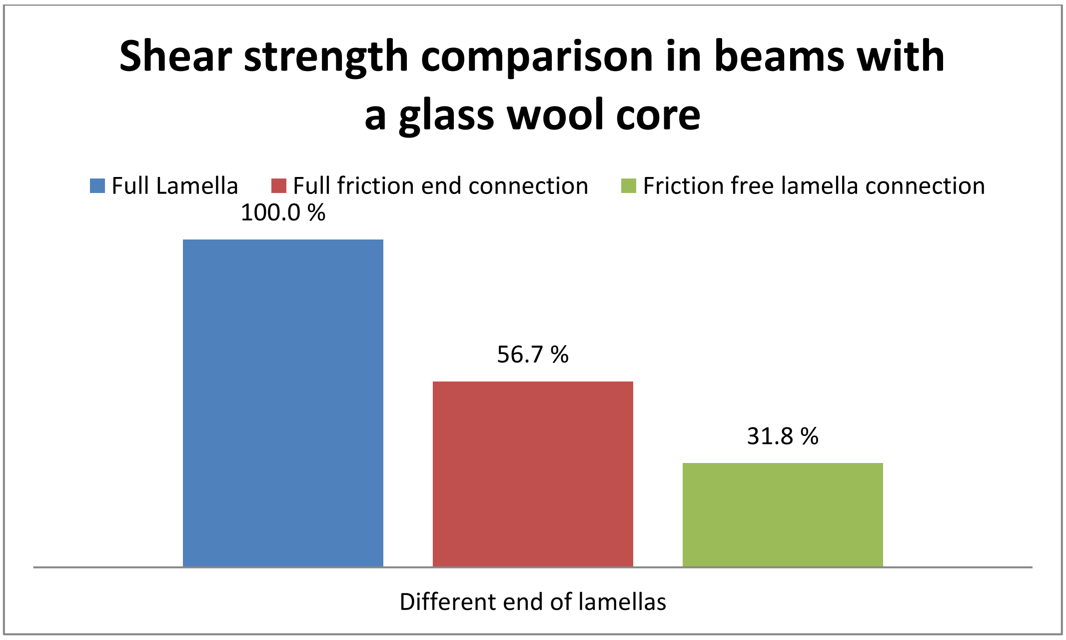


Figure 48: *The results from the glass wool reference series*

The results from the glass wool reference series are shown on Figure 48. The shear strength of glass wool is smaller and reduction from the full lamella to the lamella with some kind of end connection was smaller than in the stone wool.

The impact of the friction was assumed to be a little bit smaller in glass wool and in the full friction connection. Full friction connection was assumed to be accurate enough to calculate the effect of the face sheets.

6.2.2 End connection series

The results from the reference series were used to calculate the approximately effect of the face sheets in the total shear strength. This was done by using the equation 5.10 where the shear strength of the non-friction connection specimen was reduced from the shear strength of the full lamella specimen. In the next results, this effect was reduced and values are the shear strengths of lamellas.

The stone wool cores were the major topic of the study. The average shear strengths of the tested mechanical end connection types in lamellas are shown below on Figure 49.

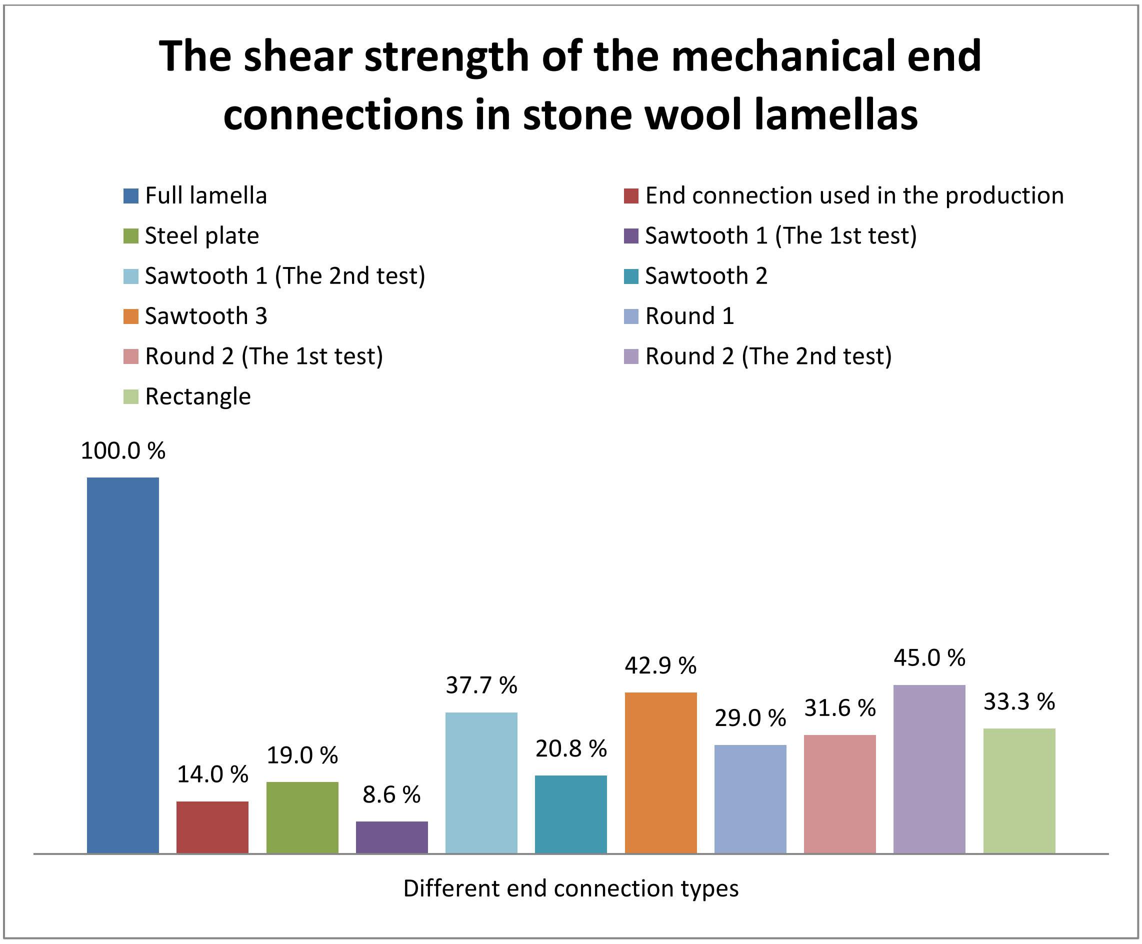


Figure 49: *The average shear strength of the tested mechanical end connection types in stone wool*

In the first mechanical end connection tests, there were gaps in some test specimens. In the first sawtooth 1 and sawtooth 2 tests those gaps existed and the results from these tests are significantly smaller because of that. The bending affected more to the end connection, but friction did not have a big impact on the shear strength. The second test with sawtooth 1 was prepared carefully and these results are more accurate and simulated better how the connection might work in full scale panels.

The sawtooth or round end connection is slightly better than the rectangle connection according to the test results. The reason might be friction which had a more effective surface on those first two connection types.

Tests revealed that it is important to have tight connections so that friction can have an effect. The bigger notches in sawtooth end connection type increased the shear strength. Nevertheless even with the bigger notches, none of the mechanical end connection types reached half shear strength of the full stone wool lamella. All the tested connection types were stronger than the end connection used in production at the moment.

The metal plate connection did not work at all. Placing the plate in the lamella was challenging. It did not succeed without a premade hole in the surface of the lamella. The metal plates were too pliable and they started to bend when the load increased enough. The plate prevented the shear failure but stiffness of this type connection was very small.

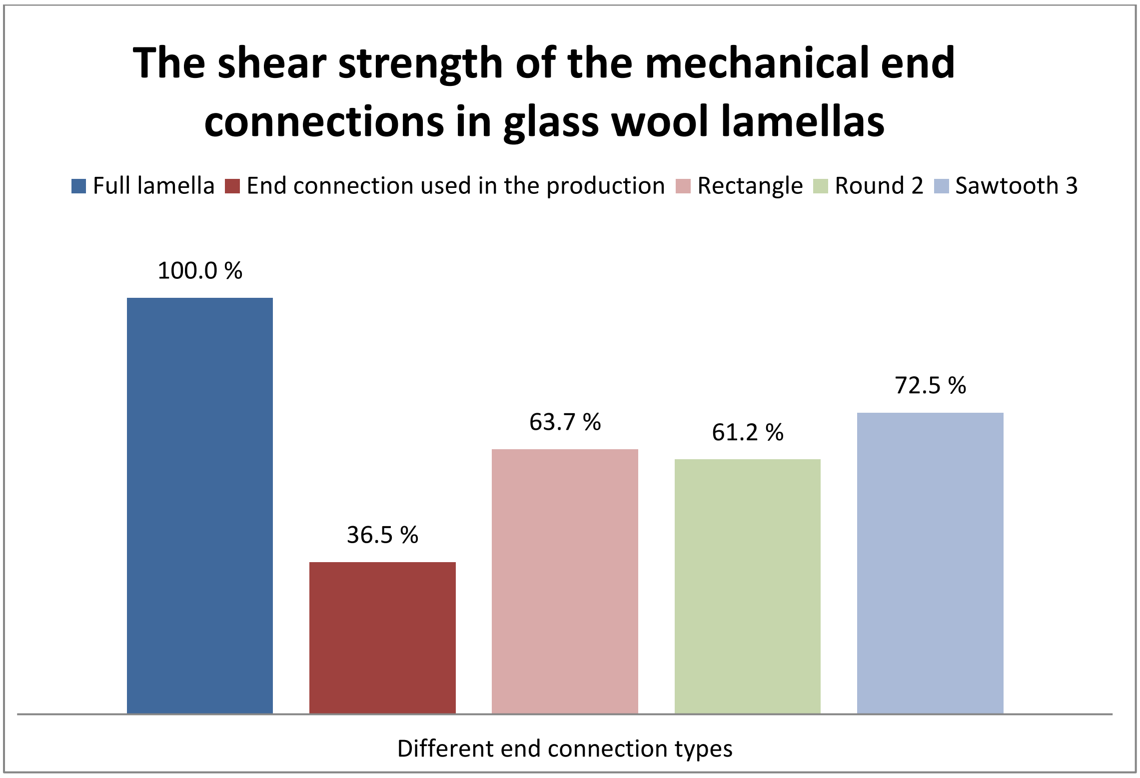


Figure 50: *The average shear strength of the tested mechanical end connection types in glass wool*

The situation was different with glass wool lamellas. Glass wool is weaker and the mechanical end connection types were relatively better than in stone wool. The results of the tested end connection types are shown on Figure 50.

All tested mechanical connection types in glass wool had almost similar in shear strength. Sawtooth was the strongest but all the types were relatively stronger in comparison with the similar connections in stone wool.

The difference in both mineral wool types was that the properly made connections worked. Even the sawtooth connection with the smallest notches had better the higher shear strength compared with the end connection used in the production at the moment.

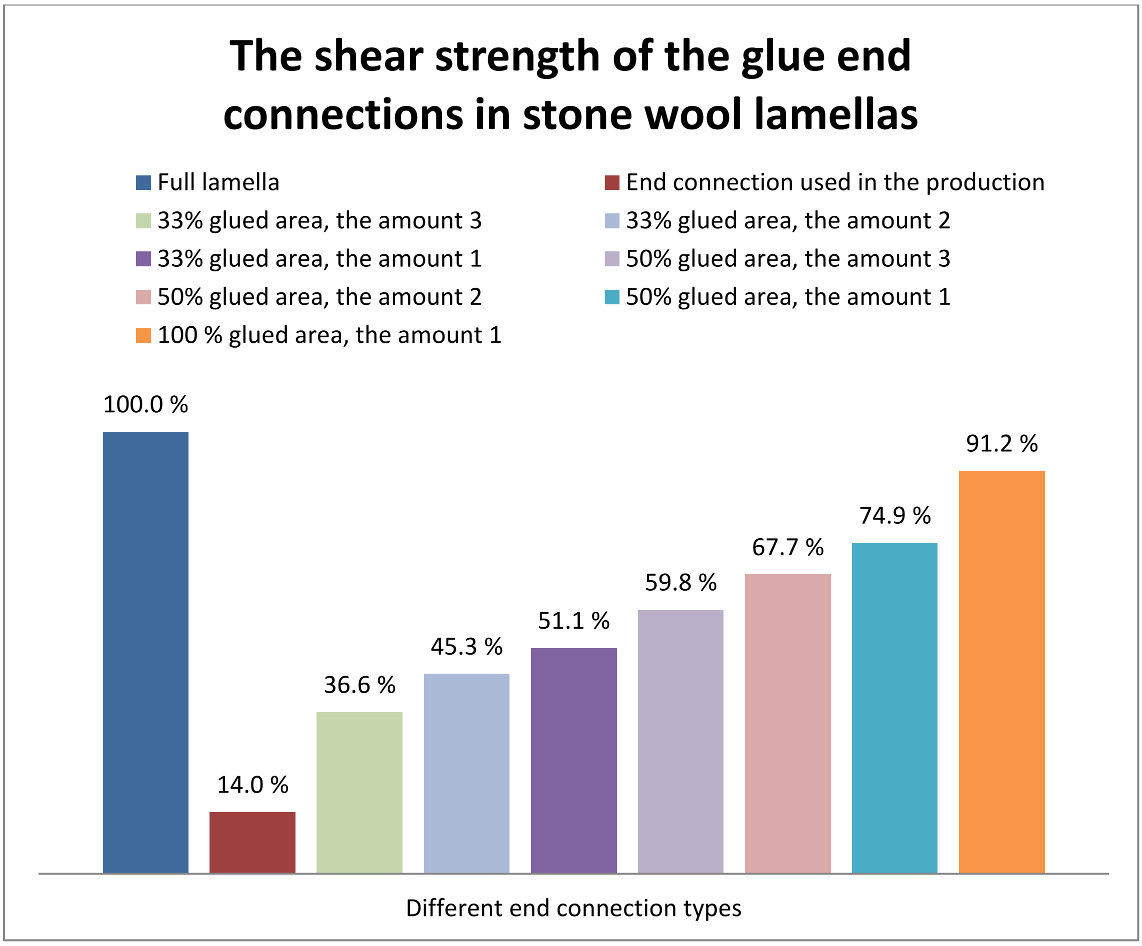


Figure 51: *The average shear strength of the tested glue end connection types in stone wool*

Figure 51 shows the average shear strength in the glue connections in stone wool. The result ensured that the size of the glue area and the amount of glue have an effect on the shear strength of the lamella.

The glue end connection can be stronger than the mechanical end connection. This requires the glue to be bonded to both lamellas. Large glued area would be not needed if the bond was good, but larger area ensured proper bonding. Similar results can be found on Figure 52.

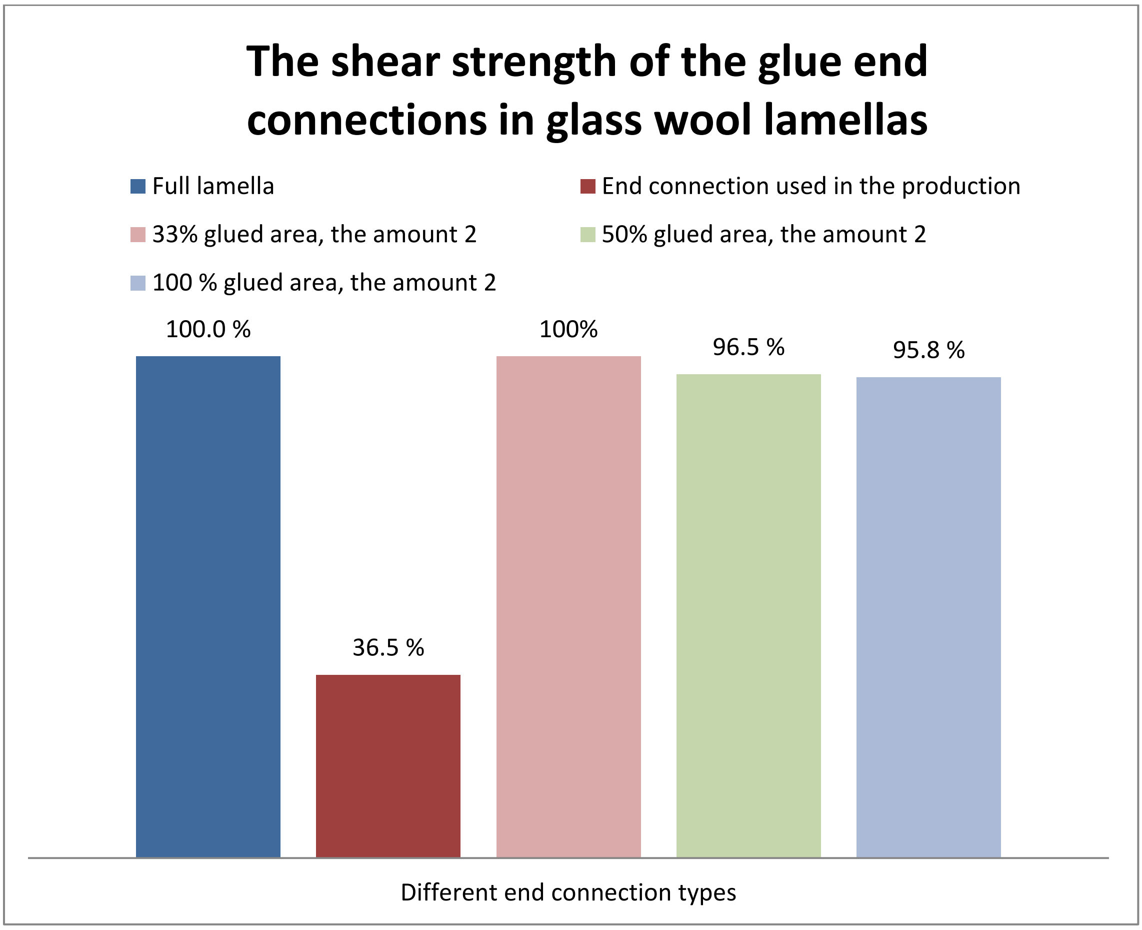


Figure 52: *The average shear strength of the tested glue end connection types in glass wool*

The glue end connections had a higher shear strength also in glass wool. Actually, they reached the same level of strength as the full lamellas. The variation in the strength of the glass wool can be seen from the results.

33% glued area was the strongest of the glue end connections. The reason might be the variation in glass wool. Glass wool used in the full lamella tests was not generally as strong as the glass wool used in the glue end connection tests. Even though that all glass wool had been taken from the same batch.

Figure 52 shows that the glue end connections are stronger also in glass wool. It might even be possible to find a glue end connection which has the same shear strength as a full lamella.

The three lamella test results supported the points made during the one lamella tests. Figure 53 shows the result of the three lamella tests. These tests were made only with stone wool and with end connection types which are reasonably usable in manufacturing. For example, sharp sawtooth forms are very challenging to make using other techniques than water cutting.

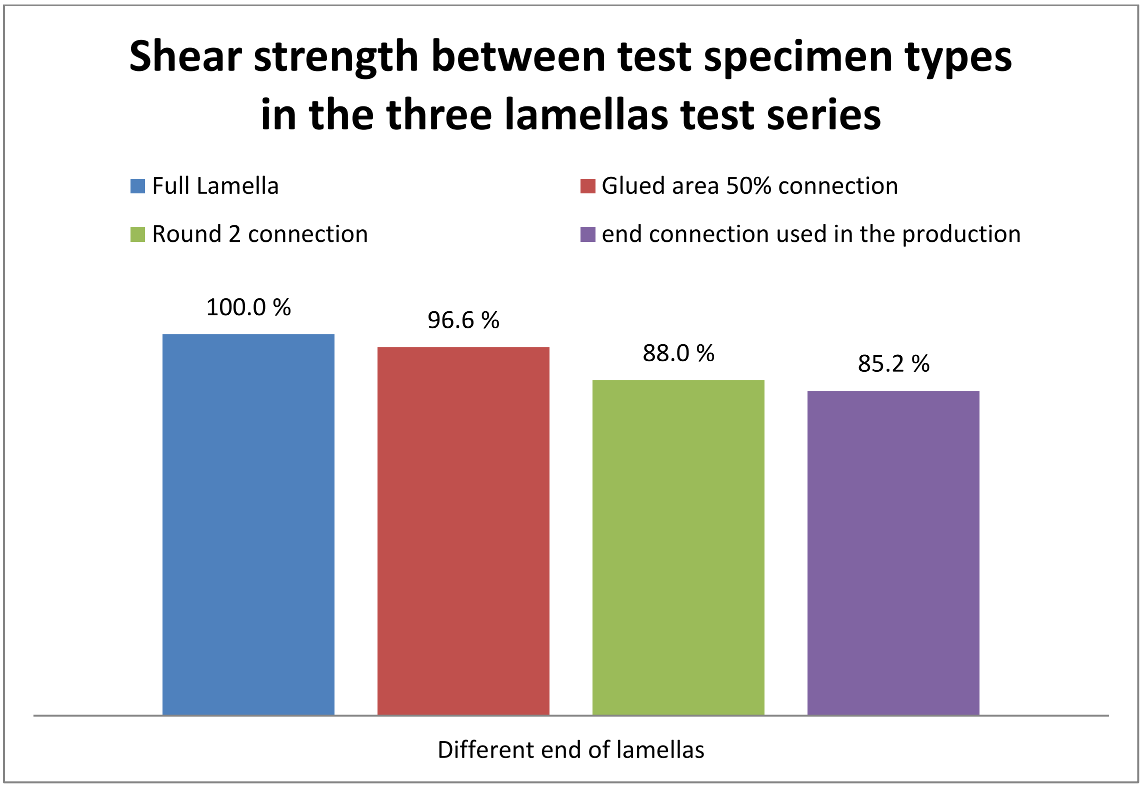


Figure 53 : *The average shear strengths of the tested three lamellas test specimens*

The results prove that in sandwich panels, the lamellas next to the lamella with end connection support this lamella. However, there was a difference between different end connections.

The straight end lamellas were the weakest of the tested types. The glue end connection was stronger than the mechanical end connection in the three lamellas test. This agrees with the results from the one lamella tests.

The stiffness of the different test specimen types was inspected during the test. The values of the force and the displacement were picked from the force-displacement curve and the relation between them was calculated. The calculated values are drawn on Figure 54

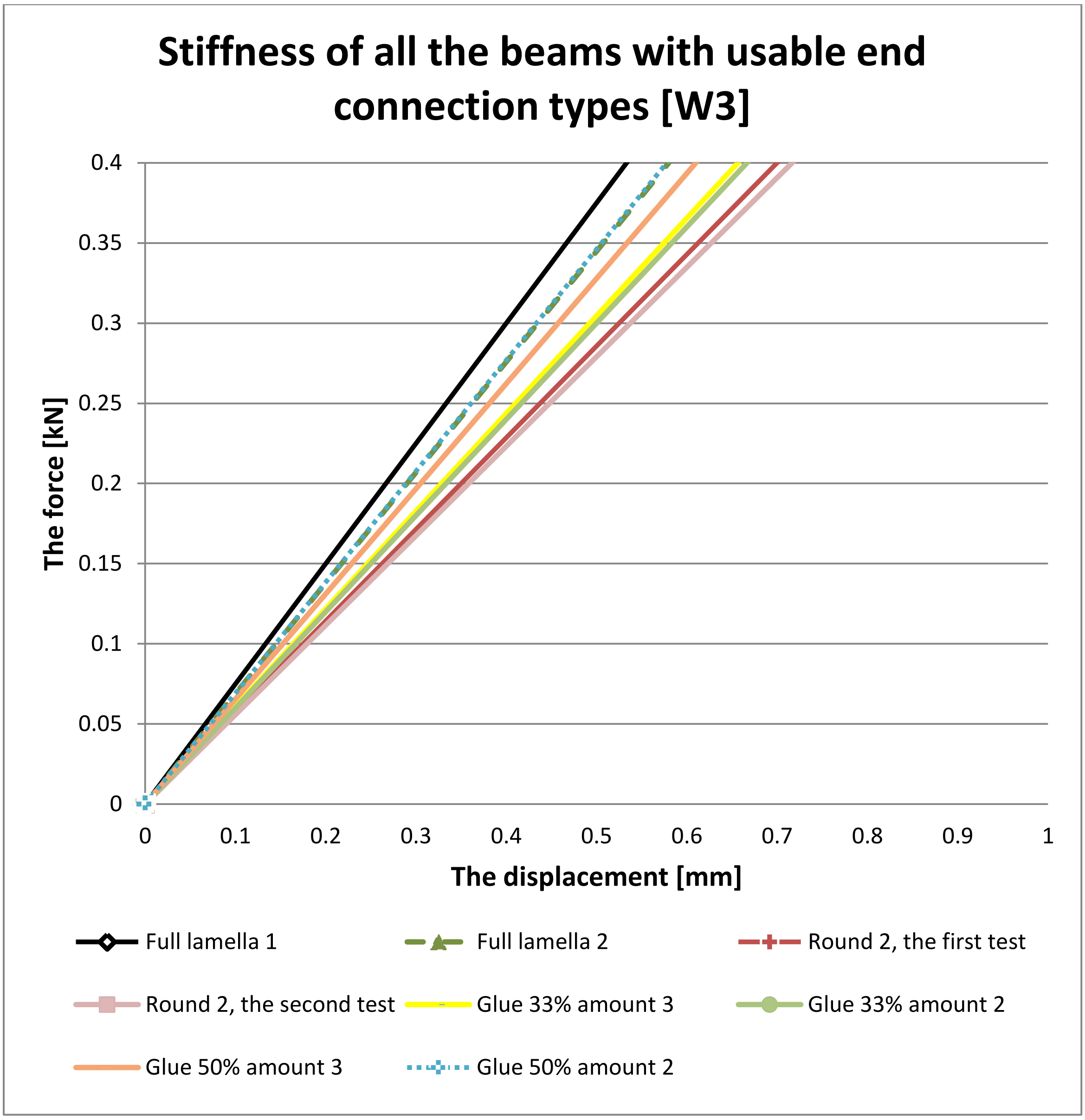


***Figure 54 :** The stiffness of the usable end connection types*

Only usable end connection types are shown here. The slope of the line represents the stiffness of the end connection. The steeper line, the more stiff the end connection is. The results showed that the glue end connections are stiffer than mechanical end connections.

6.3 Aberrations and their effect to the results

The reference series revealed that even though this test method is functional, it does not simulate sandwich panels in the production in a completely similar way. There was some difference between the test specimen and the actual sandwich panel.

The first big difference was the adhesive used between the core and the face sheets. The type of it and the amount of it were different in the test specimens. The pressure that was used after the bonding of the core and the face sheet was smaller in the test specimen preparation. Glue was spread on the mineral wool instead of the face sheet and the spreading pattern og the glue differs between tested specimens and actual panel production.

All these differences appeared in every test specimen, so they had a similar effect on the test results.

The amount of glue between the core and the face sheet might vary in different parts of the test specimen. This did not have an effect on the testing process because the purpose of the adhesive was to ensure the connection between the core and the face sheets. The shear strength of the core was significantly weaker than the strength of the adhesive connection. Failures happened in the core sooner than in the bonding.

There was also a mistake with the mixing ratio of the adhesive. A few test specimens had the face sheet attached to the core with the glue whose mixing ratio was 4:1 by the weights. In these test specimens, two-component glue was a little bit stiffer but the strength of it was still high enough. This mistake had only a small effect on the shear tests results.

In the mechanical connections, the gap between the lamellas had effect on the test results. This was discovered during the first mechanical end connection tests. After the discovery, attention was paid to the production of the test specimens.

The quality variation of mineral wool affected the test results. This was challenging aberration to take into account. It could appear without any signs and often it was noticed only from the results when the test specimen had a significantly lower shear strength than other similar specimens.

A few results were left out because it seemed that the lamella in the test specimen had a weaker point in the mineral wool. This was only reason why some test results left out.

It was possible to have mechanical end connection types which are impossible to produce during the manufacturing process. The machinery in the manufacturing process creates some limitations to the shape and size of the mechanical connection. By using the water cutting technique, it was possible to cut these forms.

The glue connections were made manually on the test specimens. This made the adhesive-wool mixture layer a little bit thicker than what it is in the sandwich panels. This layer might have an effect on the shear strength. However, it could be assumed that the friction-free connection tests isolated this effect.

In the tests, the load was divided into the load area by using plywood plates and steel rolls. This arrangement worked well but sometimes the plates and rolls had loose points between them. This affected test results slightly because some part of the total load was used to tighten these. These points were tightened first and the amount of the force was approximately 0.1-0.2 kilonewtons.

6.4 Conclusion

This thesis reached its goals; the functional test method for the shear strength of mineral wool lamellas was discovered and different end connection types were studied.

However with the stronger stone wool, the height of the specimens for testing was limited to 150 millimeters because of the test machinery. With a different machine, it might be possible to use thicker test specimens. Thicker glass wool beams and beams with weaker stone wool, however, can be tested with this test method.

The one lamella end connection tests showed that the tested end connections might improve the shear strength of the lamella compared with the lamella which has straight end connection.

According to this research, the glue end connections are the better choice if the shear strength is the only aspect that is significant. However, this research did not give the answer which is the best glue connection.

All these test results shed some light on how end connection worked mechanically in the sandwich panels. Further inspections are needed for these results to be used in the manufacturing. The manufacturing process and machinery will create some limitations as to what kind of end connection types can be used and fire safety requirements also affect as well.

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