Next Generation Façades

An analysis on the design and production of monolithic FRP composite sandwich elements for unitised façade systems

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DELFT UNIVERSITY OF TECHNOLOGY

MASTER THESIS

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Preface

This master thesis is executed as part of the master program Building Engineering at Delft University of Technology. With this research an attempt is made to provide possible improvements to the state-of-the-art of the concept of monolithic FRP composite sandwich elements for unitised façade systems, but also to the design and production processes regarding this type of element.

This research is carried out in collaboration with Scheldebouw BV, a production company specialised in the production of unitised façade systems, and currently working on the project *Municipal Office Utrecht (Stadskantoor Utrecht)*, located in Utrecht in the Netherlands. For this project a façade system is developed and produced where the bearing structure is composed of monolithic FRP composite sandwich elements. These sandwich elements correspond with the state-of-the-art as is described in this thesis.

First, I would like to thank the members of my graduation committee, Prof. Ir. Rob Nijsse, Dr. Ir. Fred Veer and Ir. Roel Schipper of Delft University of Technology, and Ir. Bas Holtus of Scheldebouw BV, for their support in all parts of the research. Furthermore, I would like to thank the management of Scheldebouw BV for providing me with the chance of executing this research. The colleagues in Heerlen from the engineering and production departments I would like to thank for providing insight in the design and production of unitised façade systems and monolithic FRP composite sandwich elements, and for helping me with the preparation and production of the test specimens that were part of the practical part of the research. Also, I would like to thank the staff of the laboratories of both the faculty of Civil Engineering and the faculty of Mechanical Engineering, who have helped me with the preparation and execution of the many real-life tests.

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Summary

As a new system in the building industry, the concept of applying monolithic fibre reinforced polymer (FRP) composite sandwich elements as bearing structure in unitised façade systems has a lot of potential compared to competing systems, but is also accompanied by a number of issues due to its novelty. Possibilities in aesthetics and improvement of the sustainability of façades makes this concept desirable for application. On the other hand, assessing the state-of-the-art of this concept, it can be concluded that the costs are relatively high compared to other unitised façade systems. Furthermore, regarding the applied materials, a lot of concessions have been made in order to meet all the requirements that are applicable for façades. With this research an attempt is made to reduce the costs and improve the overall quality of the concept by approaching this subject from three different angles, which are discussed in three separate parts. These parts are the system analysis, in which the focus is on analysing all aspects of the concept, the material assessment, where the predictability of the material behaviour is the main subject, and finally the quality assurance.

System analysis

First the concept and all its interdependent factors and influences are analysed. FRP composites are one of the most difficult materials to design and work with, and as it is applied in monolithic sandwich elements in combination with external influences and requirements, the subject becomes even more complex. Furthermore, compared to the high-performance composites that are used in the aerospace industry, very little research is done regarding the general behaviour and material properties of the cheaper engineering composites that are used in the building industry. The currently applied concept results to a large extent from an ad hoc working method. Analysing and documenting the interdependent relations can lead to optimisations in the design and production processes with fewer concessions, for example by increasing the integrity or durability of the elements. The factors that are of influence on the concept are divided into six groups, namely materials, production process, critical components, technical specifications, shape

and design, and environment. From this analysis four factors take in a critical position within the development of the concept. The most important and most obvious one is the matrix, which is in contact with all other materials and layers in the element, and is also responsible for the integrity of the FRP composite material and therefore for the entire sandwich element. The other three key factors are the flammability of the sandwich element, especially of the applied polymeric compounds, the production process with in particular the conditions during the production of the monolithic sandwich elements, and the connections between the sandwich element and the critical components.

Additional to the factors and influences that accompany the concept, reviewing the state-of-the-art of, and applying the design for manufacturing and assembly methodologies on the concept, an attempt is made to make optimisations to the concept, thereby reducing the costs and improving the quality of the concept. This assessment shows that the current solution for obtaining sufficient fire resistance, which relates to the second key factor, has far-reaching consequences regarding the cohesive and adhesive properties of the matrix, and thus on the integrity and durability of the element. It must be noted that with the currently available information the exact effect is near impossible to quantify. Applying alternative materials for the same solution or adding an extra layer between the finishing and structural layer have the potential to nullify these negative influences to a large extent. However, both options do require additional research before these can be introduced into the concept.

Material assessment

Secondly, attention is paid to improve the predictability of the material behaviour of the structural layer in monolithic FRP composite sandwich elements. The material assessment comprises an analysis on the engineering constants that are required to be known during the design phase, as well as testing standards and analytical methods designed to determine these constants. An analysis into the structure of monolithic FRP composite sandwich elements, and how this type of element transfers the loading it is subjected to during service, resulted in the required engineering constants. Interestingly, the required material properties of the structural layer are not limited to tensile and compressive behaviour, as is with standard sandwich elements, but also its shear behaviour is necessary to be known. Currently standard procedure is to ascertain material properties of FRP composites by executing a vast range of physical tests, ranging from the basic tensile tests up to accelerated weathering tests in order to predict the durability of the finishing layer. These tests are executed according to test standards, both ASTM standards and ISO standards are possible, but the amount of tests required makes obtaining the necessary engineering constants a costly and time-consuming process. In order to improve the predictability of engineering composites, and thereby reduce the costs regarding the testing process, existing analytical methods are compared with test results from tensile, and in-plane and out-of-plane shear tests. These comparisons show that with the assessed methods most moduli of laminae with oriented fibre reinforcement are actually predictable to some degree. Overall the Halpin-Tsai method presents the most accurate predictions for the tensile and in-plane moduli, compared to the methods prescribed by the Rule of mixtures and Chamis equations. None of the assessed methods present a verified possibility to assess the strength of the laminae, with exception of the Rule of mixtures. The accuracy of this method regarding the prediction of the tensile strength of unidirectional fibre reinforced laminae is nowhere near accurate. On the other hand applying this method for the determination of the in-plane shear strength presents a considerably accurate prediction.

Quality assurance

The third part of the research focuses on quality assurance regarding the production of monolithic FRP composite sandwich elements. The quality of FRP composite materials is sensitive to outside influences during production. The local environment and the presence of manual labour in the production process can cause inconsistencies in the laminate and add contaminations to the matrix. Also, the FRP composite laminate is covered with a finishing layer, making the detection of errors nearly impossible. Only major damages and irregularities visible at the surface may cause a flawed element to be rejected. Other faults within the structure can be overlooked and may cause failure when the element is in service. Besides producing with skilled labour, the most important regarding the prevention of at the surface undetectable flaws and inconsistencies is to provide a clean working environment with a consistent local climate. Furthermore, the design process has a significant influence on the quality of the FRP composite containing building components since it determines the level of difficulty of production. Complex shapes and the application of infill-blocks in the moulds not only increase the costs and create additional work, it also increases the chance of flaws and failure.

Considering the quality control of the raw materials, the production process and the end-products, one of the main problems is that during production some of the materials need to be mixed before application. The quality control on the to be used resin is actually impossible without executing expensive tests, such as gas chromatography. Also the quality of the fibrous material is difficult to verify. An easy solution for this problem is to produce reference laminates with each sandwich element that contains the same fibre reinforcement and matrix material. Test specimen can be cut from this laminate and the quality can be tested without interfering in the production process itself. The downside is that if a test specimen shows below standard results the façade element already is produced. As for the quality control of the production process, it is advised to follow an accurately compiled checklist for each step of the production process due to presence of manual labour in the process. The tasks themselves may not be very difficult, but the effects of variations during these tasks are easily underestimated and can have a large impact on the quality. Additionally, the conditions during production are of influence on the appearance and performance of the end-product. This makes it important that both the conditions in the production facility and the cure and post-cure process are kept consistent during the manufacturing of all elements that are part of a single project.

Research evaluation

The system analysis shows that some of the aspects in the first three discussed groups, the materials, production process and critical components, are key factors in the entire process, namely the matrix, the fire behaviour of the element, the production process and its exact execution, and the connections with the critical components. The analysis results in the conclusion that these key factors have a significant influence on the durability of the element, both positive and negative. Currently available technology, which is reviewed during the system analysis, present feasible solutions for issues that emerged during the review of the state-of-the-art, but also improvements on other aspects, which may reduce the overall costs.

The outcome of the material assessment is that parts of the discussed methods are potentially usable for calculating most of the in-plane moduli of FRP composite laminae. On the other hand, the various strengths of a lamina are more difficult to ascertain, and determination of engineering constants is principally avoided by the existing methods. Overall, the Halpin-Tsai method displayed the most coherence with test results from engineering composite specimens. Further development of a calculation method for engineering composites would decrease the number of necessary tests significantly, thereby saving time and money.

The design, the applied materials and the execution of the production process all determine the quality and durability of the elements. Defects in the produced sandwich elements that are caused by any of these three sources do not necessarily have to show themselves on the surface of the element. With a visual inspection the large defects can be spotted, the internal errors require non-destructive testing (NDT) methods of which ultrasonic testing methods are the most feasible for sandwich elements. The prevention of errors requires a strict quality control program that consists of an extensive checklist for both the execution of the production process and the materials, covering each step and condition.

The recommendations resulting from this research relate to a large extent to the conclusions drawn from every part of the study. Most pertinent is the development of a balanced interaction between the applied matrix and a sufficient fire resistance of the element. Another aspect of the concept that requires further development, and which allows for improvement in quality and durability of the entire element is the anchor system. Last but not least is the development of an all-encompassing analytical calculation method for engineering composite laminae. In contrast with the other two recommendations, this proposition requires much more effort to complete. Short term improvements in predictability of the material may be expected and even implemented in the design process, a complete method requires more time and resources. As with guidelines and calculation methods available for steel and concrete, in time knowledge will grow to a near full understanding and a complete method will be compiled for engineering composites. However, this can be assumed to be a too big of a task for a single company and is more suitable for a group of companies and/or institutions, or an umbrella organisation.

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Symbols and Abbreviations

Latin symbols

A	Area	[mm^2]
b	Width of the plate or beam	[mm]
b'	Adjusted width: Distance between the centroids of the face layers covering the sides	[mm]
b_c	Width of the core of a sandwich plate or beam	[mm]
D	Rigidity	[Nmm^2]
E	Tensile modulus	[N/mm^2]
F	Concentrated load	[N]
f	Strength	[N/mm^2]
G	Shear modulus	[N/mm^2]
HDT	Heat deflection temperature	[°C]
h	Height of a plate or beam	[mm]
h'	Adjusted height: Distance between the centroids of the face layers	[mm]
h_c	Height of the core of a sandwich plate or beam	[mm]
I	Moment of inertia	[mm^4]
K	Bulk modulus	[N/mm^2]
k	Shear coefficient for elements in flexure	[–]
L/l	Length	[mm]
M_R	Modulus ratio	[–]
m	Mass of material in specimen (thickness not included)	[kg/m^2]
R_c	Thermal resistance	[m^{2}K/W]
r	Radius	[mm]
T_g	Glass transition temperature	[°C]
T_{ig}	Ignition temperature	[°C]
t	Thickness	[mm]
v	Volume fraction of material in specimen	[%]
w	Deflection perpendicular to the plane (z-direction)	[mm]

Greek symbols

α	Coefficient of thermal expansion (CTE)	[K^{-1}]
β	Factor	[–]
γ	Engineering shear strain	[rad]
γ_M	Material factor	[–]
ε	Axial strain	[%]
θ	Rotation of fibre orientation relative to 1-direction	[°]
κ	Curvature	[mm^{-1}]
λ	Thermal conduction coefficient	[W/(mK)]
μ	Dynamic viscosity	[Pa $\cdot$ s]
ν	Poisson's ratio	[–]
ξ	Halpin-Tsai constant	[–]
ρ	Density	[kg/m^3]
σ	Axial stress	[N/mm^2]

Latin indices

c	Core layer
cp	Composite
cs	Cross-section
cr	Creep
$corr$	Correction
d	Compression
f	Face layer
fat	Fatigue
fr	Fibre
i	Inner
max	Maximum
min	Maximum
mx	Matrix
o	Outer
s	Surface
t	Tension
tot	Total
u	Ultimate
V	Shear

Greek indices

γ	Shear
κ	Flexure

Coordination

$1, 2, 3$	Direction on Principal Material Coordinate system
x, y, z	Direction on Cartesian Coordinate system

Abbreviations

ASTM	American Society for Testing and Materials
BMI	Bismaleimide
CFM	Continuous filament mats
CLT	Classical lamination theory
CNC	Computer numerical control
CSM	Chopped strand mat
CTE	Coefficient of thermal expansion
DMA	Dynamic mechanical analysis
DSC	Differential scanning calorimetry
EP	Epoxy
FRP	Fibre reinforced polymer
ISO	International Organization for Standardization
LRTM	light resin transfer moulding
NDT	Non-destructive testing
PF	Phenol-formaldehyde or phenolic
PU	Polyurethane
QA	Quality assurance
RFI	Resin film infusion
RTM	resin transfer moulding
TERTM	Thermal expansion resin transfer moulding
UP	Unsaturated polyester
UD	Unidirectional
VARTM	vacuum assisted resin transfer moulding
VE	Vinyl ester

Chapter 1

Introduction

Fibre reinforced polymer composites, or FRP composites in short, are relatively new in the building industry. In the building sector this material was initially applied as additional reinforcement for concrete elements, up to the moment that complete structural elements were made of composite materials. However, this line of materials is only used for these kinds of applications for about 60 years[1]. FRP composite materials are only recently applied in façades. In the beginning the material was used in order to get a specific architectural effect on the outside of the building or in order to reduce weight. Due to the freedom in form and the relative low density of the material the possibilities for this application are endless, figuratively speaking. A more recent trend is to construct entire façade elements of FRP composite materials.

There are multiple ways to construct unitised façade systems with FRP composite (containing) components, which can be split into two general methods. The first method is to assemble façade elements of multiple (FRP composite) components. This is a similar process compared to the fabrication process of aluminium-frame unitised façade systems. The second method, and that is what the main subject of investigation is in this thesis, is the production of the entire façade element out of one major (monolithic) FRP composite based component in a single production process. With this method the FRP composite sandwich element functions as both the bearing framework of the façade element and the insulated infill panels, while it is only one component. An example of such an element is shown in Figure 1.1.

The idea behind unitised façade elements is that these are completely produced and assembled off site. After transportation the elements are mounted on the bearing structure, creating an instantly finished façade. The main advantage of this system is that the installation speed of the façade is very high, and the quality of the elements is also very high as the elements are produced and assembled in a controlled environment. Secondly, since a monolithic FRP composite element

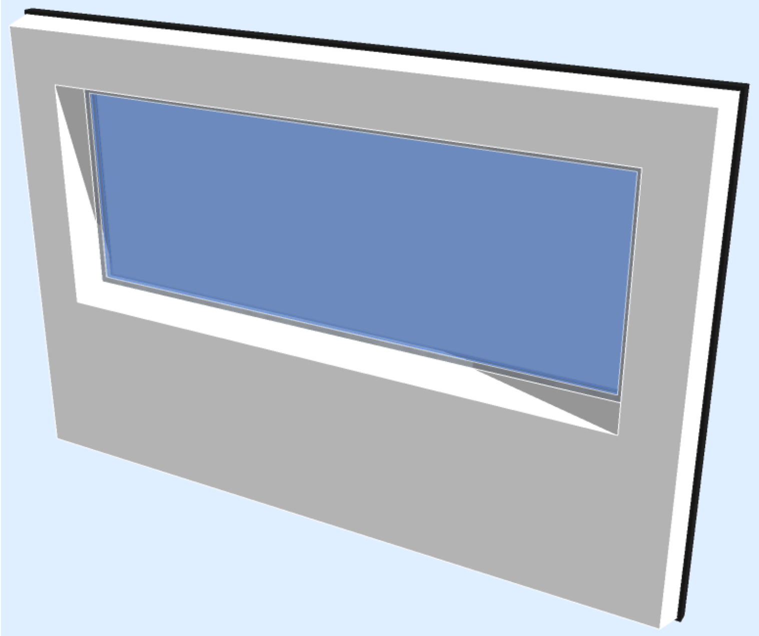

Figure 1.1: Example of a unitised monolithic FRP composite sandwich façade element

consists of only one part, the amount of connections is significantly lower compared to other façade systems. There are, however, additional components required in order to make a complete unitised façade element. First of all one or more windows need to be installed. Furthermore, a sealing needs to be applied around the element in order to let the installed elements connect to each other and create a weather-tight façade. Also the FRP sandwich elements need to be supplied with a mounting system for easy instalment on site. The separate components are shown in Figure 1.2.

The material itself and this specific technical development are still in its infancy. Much can be improved on the predictability of the properties and behaviour of the material. Also designing and fabrication processes concerning these structural elements can be improved to attain an end-result of higher quality.

1.1 A brief overview of the subject

One of the main reasons to choose for FRP composite sandwich elements for unitised façade systems is the increase in freedom in design. The shapes that are possible to be made with FRP composite sandwich elements are principally endless. For instance, this system allows the façade to follow a double curved or

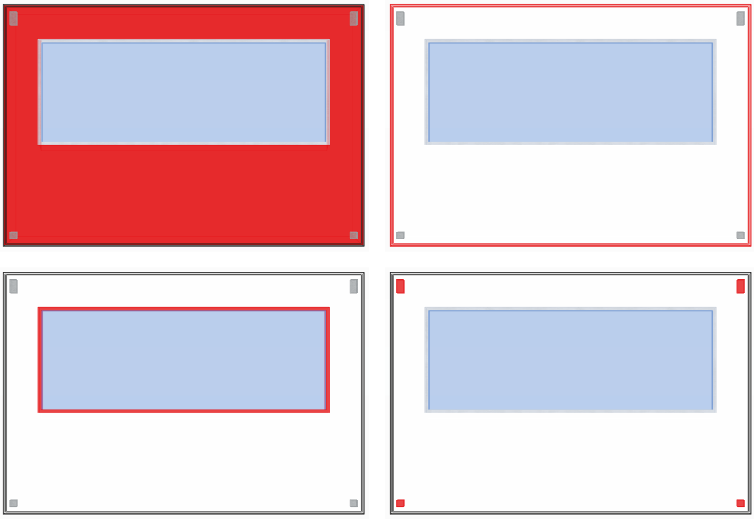

Figure 1.2: Overview of components (highlighted in red): FRP composite sandwich element (upper left), sealing (upper right), window (frame) (bottom left), anchor construction (bottom right)

twisted plane. Another important feature of this system is that it allows for better thermal insulation compared to other façade systems. Furthermore, concerning the production of the façade elements, a monolithic FRP composite sandwich element is finished as soon as it is removed from the mould, optionally including the finishing layer on both sides of the element. This reduces the complexity and duration of the assembly of the façade elements. However, considerations, or influencing factors concerning the design and production process of such elements, are numerous, and the mutual dependence of these factors is very high. These factors and their relations are visualised in Figure 1.3. The interdependent factors are grouped and briefly described below.

- Materials Composite Sandwich: Core material, fibre material (type of material and type of fibre form), matrix composition, finishing (interior and exterior);

- Production Process: Duration, required manpower and –hours, required moulds, mould material and additional tools, necessary precautions (safety measures), indoor climate;

- Critical Components: Sealing (between the façade elements), mounting of glass surfaces (structurally glued glass and in aluminium framed glass), anchor construction;

- Technical Specifications: Structural specifications, building physics, fire behaviour, additional specifications (set by the client);

- Shape and Design: Shape (composite sandwich framework or panel), design (colour, gloss, shape, etc.), durability (resistance against external / environmental factors), consistency (little to no difference in appearance between unitised elements due to production process, etc.);
- Environment: Environmental impact and energy efficiency (materials used, production process, in use on building, end of life-cycle), other gains and losses considering the environment.

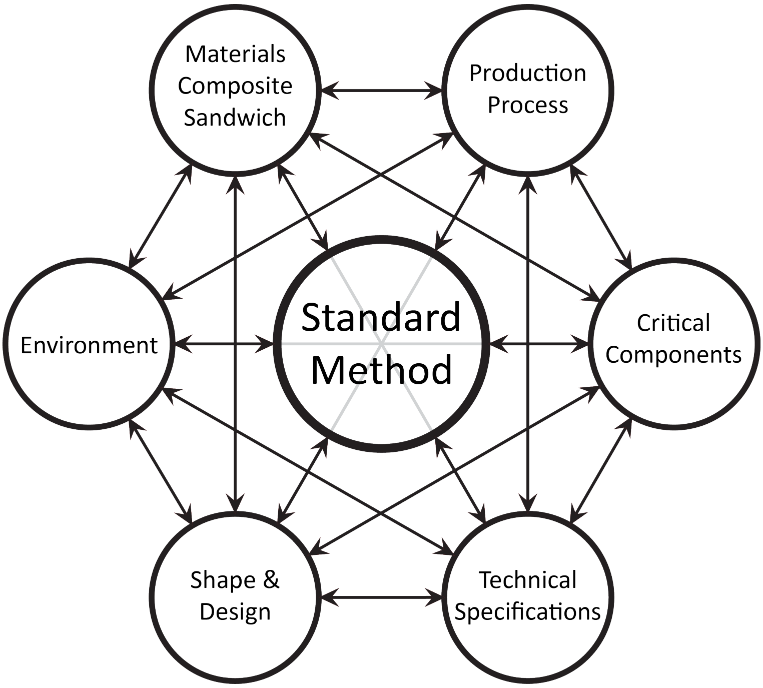
Materials
Composite
Sandwich
Production
Process
Environment
Standard
Method
Critical
Components
Shape &
Design
Technical
Specifications

Figure 1.3: General overview of the interdependent factors

1.2 Problem analysis

Since FRP composites are available for just over a century, and commercially used in the building sector for less than half this time, there are still a number of major difficulties in the application of this material. The first problem is the lack of legislation and quality standards, mainly due to the novelty of the material. Also the large diversity in possible compositions of this material makes FRP composites an at least as complex material as for example concrete. The complexity and workings of the entire system is hard to fathom, especially when it concerns the effects of long-term and dynamic loading, and the effects of exposure to the elements. These material features are rather scarcely tested and documented. An additional problem to this matter is that contractors have little to no experience in and knowledge of the utilisation of FRP composites. The required knowledge, such as structural designs and calculations, are bought in from specialised companies, which mostly have gained experience in the aerospace, automotive and maritime industries. There are however major differences in requirements between these industries and the building industry. First of all façade elements are subjected to a different loading and environment, and the materials used and the production processes applied are also generally different than what is standard in the other industries. One of the main resulting concerns here is the durability of FRP composite materials, this is exacerbated by a lack of research data on this subject applicable for construction elements such as façade elements. Furthermore, the engineering of the building envelope is subjected to a large amount of by law enforced requirements, a large variety in design and shape within a project, and generally a relative low available budget. Consequently, the choices made during the design phase often have a negative influence on the quality, durability and performance of the final product[16].

As is previously mentioned, there is very little legislation present when it comes to FRP composites as a material in the building industry compared to other construction materials, such as steel and concrete. For the general requirements, regarding governing loads and building physics, in the Netherlands the Dutch Building Decree is applicable in combination with corresponding European standards. Concerning for FRP composites applicable material and production process dependent safety factors much less legislation is available. In 2003 the Dutch organisation CUR Bouw & Infra has published a guideline dedicated to FRP composite materials in the building industry (CUR aanbeveling 96). This guideline is still limited to the application of glass fibres in the composite material. Other fibrous materials, such as carbon, aramid, basalt and natural fibres, are not discussed. More extensive handbooks that are available are the European Eurocomp Design Code and Handbook and the German BÜV-Empfehlung. Also in these handbooks the focus is mainly on glass fibre reinforced composites.

The main downside of the currently available guidelines and handbooks is that is assumed that the properties of the composite material used are known in advance. Officially these properties can be attained only by physical testing according to the corresponding testing standards. There is no generally available and accepted calculation method known, with which the material properties of FRP composites can be accurately determined, or at least approximated, independent on the composition of the composite material. Companies specialised in composite materials often work with values obtained from previous experience and/or assumptions. The values that are gained from previous experience are material (combination) specific and do often not apply when the composition of the composite material is changed. Assumed values of the properties of composite materials are only a rough approximation, and often not accurate and also very conservative, which may lead to a distorted view of the reality. Here it must be taken into account that the production method, the conditions during production and the curing process have a significant impact on the mechanical properties of the composite material.

Another important issue is that any regulation or certification for the application of FRP composites in the façade branch, as there is for example for aluminium framework based façade elements (VMRG certification), is missing. Such certification leads to the production of elements of a specific minimum quality and a guarantee for a certain period. Concerning FRP composites in façade elements this would have a large impact on mainly the durability and long term quality of the aesthetics of the elements.

1.3 Research setup and scope

The research done on this subject should present a usable method that can be followed during the design and production phases of monolithic FRP composite sandwich elements for unitised façade systems. This method will not show a completely standardised system, but more an optimisation of a design and production process and the choices that are involved, or in other words an improved working concept. It is of course of importance that the presented method still meets the minimum requirements that are set by law, and allows for design choices and additional requirements, set by the client.

1.3.1 Objectives of the research

The main objective of the research is the direct result of the analysis of the subject:

"The development of a standard method for the design and production of monolithic FRP composite sandwich elements for unitised façade systems."

The main objective can be split into several intermediate objectives:

1. Describe the influences, impact, and requirements of the interdependent factors that are applicable to the design and production of FRP composite sandwich façade elements;
2. Assess the most critical factors of the design and production process of the FRP composite sandwich façade elements;
3. Discuss and substantiate the optimal combination of materials and production process, and determine an acceptable approximation of the design values of the mechanical properties;
4. Verify the possibilities and limitations of the material and production process applicable for the design of the elements;

5. Assess the required precautions and control tests to guarantee a certain level of quality.

1.3.2 Research questions

The main objective and the problem analysis lead to the following main research question:

"Is it possible to ameliorate the design and production process of current systems consisting monolithic FRP composite sandwich elements with currently available knowledge, technology, and materials, thereby improving the ease and flexibility in design, and improving the quality and reducing the costs of the finished product?"

This main research question can be solved by approaching the problem in three phases. The first set of sub questions make up a theoretical approach to the problem, with which a systematic assessment can be made of the entire design and production process of FRP composite sandwich façade elements:

1. Which factors influence the choices made in the design and production process of FRP composite sandwich elements?
2. What are the pre-set specifications and minimum requirements of the interdependent factors?
3. On which of the other interdependent factors has a specific factor influence?
4. What is the impact of the change of a factor on the other interdependent factors?
5. Which interdependent factors assume a critical position in the overall design and production process?

The second set of sub research questions focuses on a specific part of the process, namely on the combination of materials and production process. These questions require the results from the first set of sub research questions and substantiation from practice:

6. What combination of materials and production process is possible, with which the minimum requirements (Dutch Building Decree & European standards) can be met and still allows for flexibility in design?
7. What are the possibilities and limitations of FRP composite materials concerning the production of the façade elements?
8. What are the material margins and limits required to be known in the design phase?
9. Which existing method or model can be used to improve the predictability of the properties and behaviour of the FRP composite material in the sandwich elements?

With the third set of sub research questions the results of the first and second set are processed and evaluated. Furthermore, with the answers to these questions a setup can be made for the quality assurance of such façade elements before, during, and after the production of the elements:

10. What steps are required to assess the quality of the materials before and during processing, using this specific combination of materials and production method?
11. How can the overall quality of FRP composite sandwich façade elements be guaranteed?

1.3.3 Scope of the research

In order to cover all aspects of the design and production process, the research is divided into three parts. The first part of the research focuses on the analysis of all interdependent factors. This leads to an overview of the relations between and impact of the relations of the factors, including an assessment of the necessary requirements, and a prognoses or indication of the corresponding costs or cost differences when possible. The overview of interdependent factors shown in Figure 1.3 visualises the complexity of the subject and all that is involved. The second part, which is based on the choices in material combination and production process of the first part, focuses on the predictability of FRP composites as a construction material. A number of tests covering a range of material compositions make it possible to assess the applicability of one or more existing calculation methods for the material. The third part of the research focuses on the failure methods and quality of the FRP composite material and the resulting façade elements. Necessary preparations before production starts, checks during the production of the elements and verifications after the elements are produced need to be documented in a quality assurance program.

The focus in all three parts of the research is mainly on the FRP composite material in the sandwich elements and the FRP composite sandwich element as a whole, though the combination with the other components in the façade element is also assessed. The aim of the research is to improve the overall quality and durability of the elements, streamline the design and production processes, and to reduce the overall costs, in other words, an improved working concept as a whole.

Part I

System Analysis

Chapter 2

State-of-the-Art

In some current and finished building projects monolithic FRP composite sandwich façade elements are already applied. The composite material used in these façades is based on E-glass fibres and an unsaturated polyester resin, mainly due to the low cost of this material combination. The core of the sandwich panel is made of PIR (Polyisocyanurate) or a similar low density foam. However, the elements applied in finished and current projects have two major downsides. Firstly, and obviously for manufacturers the most important one, the average cost per square meter is very high compared to other façade systems. Secondly, currently applied production methods and available materials do not allow for the sandwich element to be completely produced at once, including both the interior and exterior finish, while the elements still comply with all the requirements concerning structural specifications, building physics, and fire behaviour. Especially the fire behaviour (flammability and smoke production) is a problem for polyester resin based composite materials, since this resin is quite flammable. Other resins also show relative poor fire behaviour. For example, epoxy resin has a very high smoke production.

A design and production analysis that takes all influencing factors into account is currently not available. Information about engineering composites with relative low fibre volume fractions is scattered and only limited available. Current methods are more trial-and-error based. Similar trial-and-error based methods are used to obtain the material properties of FRP composites. For every new composition of an FRP composite laminate tests are executed to acquire the design values of that specific composition. Solving the problems that occur in practice during the design and production of FRP composite sandwich elements, ad hoc changes are made to the design or the composition of the composite material. However, seemingly small changes often have unexpected large impacts on other factors. A change in the composition of the composite material, such as increasing the amount of additives meant to improve the fire behaviour, can have a minor or major influence on any other material property, for example the strength, adhesion and viscosity of the resin. The effects of such changes arise in a later stage, where the material or element is subjected to physical tests.

The result of a trial-and-error based design and production process does not necessarily lead to an optimal performing final product for the lowest price. A complete analysis of all influencing factors would lead to a better understanding of the interdependent interaction of the factors, and a more structured approach and better informed decision making during the design and production phase. This will most likely result in a better performing, more reliable and higher quality final product for lower costs.

Chapter 3

System and Process Overview

FRP composite material on its own is a complex subject. The variety in and collaboration between the fibre reinforcement, resin (matrix) and additives lead to an enormous amount of possible combinations, which each lead to a composite compound with a unique combination of material properties. Furthermore, the material properties of each compound may be experienced as positive or negative depending on the application it is meant for, and may behave differently dependent on the environment it is subjected to. Consequently, a full iterative analysis of all interdependent factors, as is discussed in the introduction, is a considerably comprehensive task and would take a large amount of time and effort to complete. Therefore, the system analysis follows the interdependent factors in a certain sequence in order to swiftly filter out the options that are not likely, efficient or possible to combine, or do not meet the requirement or a desired level of flexibility. This process is a reshaped version of Figure 1.3 and visualised in Figure 3.1.

The setup of the system analysis makes it possible to discover the factors that have a critical position in the design and production process, and to narrow down the available options for the design and production process. Throughout the analysis the impact of the interdependent influences is substantiated thoroughly and quantified where possible. The main intent of this process is to lead to an improved combination of materials and production process. The important criteria during the analysis are reducing the complexity and overall cost of the development and production of FRP composite sandwich elements, and to achieve a durable and reliable end-product of high quality.

The following six chapters each discuss one of the groups in the order that is presented in Figure 3.1. This part of the research ends with a chapter containing an overview of the system analysis and potential optimisations.

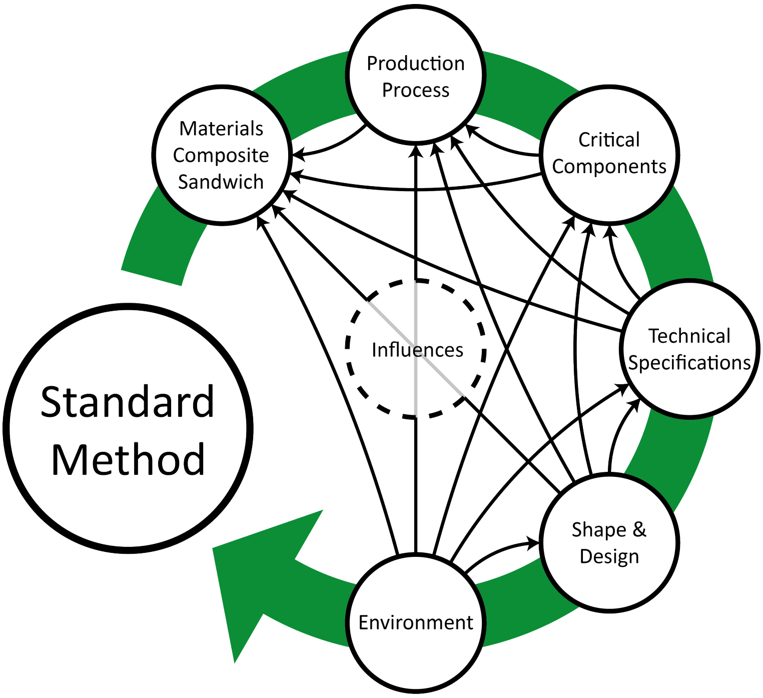
Production Process
Materials Composite Sandwich
Critical Components
Technical Specifications
Influences
Standard Method
Shape & Design
Environment

Figure 3.1: Graphic overview of the analysis process

Chapter 4

Materials in FRP Composite Sandwich Elements

FRP composite sandwich elements consist of three main layers, namely the core, the face layers and the finishing layer. For all three layers a wide variety of materials is available. Then again, all materials do have to work together properly in order to guarantee the structural integrity of the element. The causes the materials to have a major influence on each other. This chapter starts with the analysis on the properties and behaviour of the materials separately and combined. Consequently, influencing factors of the production process, critical components, technical specifications, shape and design, and the environment in relation with the materials are assessed separately in that order.

4.1 Materials and material interaction

By default FRP composite sandwich elements consist of a relative soft lightweight core with on both sides an FRP composite face layer. The core layer gives the sandwich element its high thermal resistance, and by holding the two face layers in place at a specific distance from each other, it increases the flexural rigidity of the element. The face layers are the components that give the element its strength.

In case of self-bearing monolithic sandwich elements, which are required for façade elements, the core layer is completely enwrapped with a layer of FRP composite material. In this case the composite layer can be seen as the structural skin of the element. The finishing layer covers the entire surface area of the sandwich element, thereby protecting the composite skin and core against exterior influences, and provides the element its desired aesthetics. This layer generally consists of a gel coat or a layer of lacquer. The structure of a self-bearing sandwich element is shown in Figure 4.1. All three layers interact with each other and are bonded by the matrix used for the FRP composite skin. It is therefore of the utmost importance that the materials used are chosen carefully. For each of the layers the most commonly applied materials will be discussed briefly.

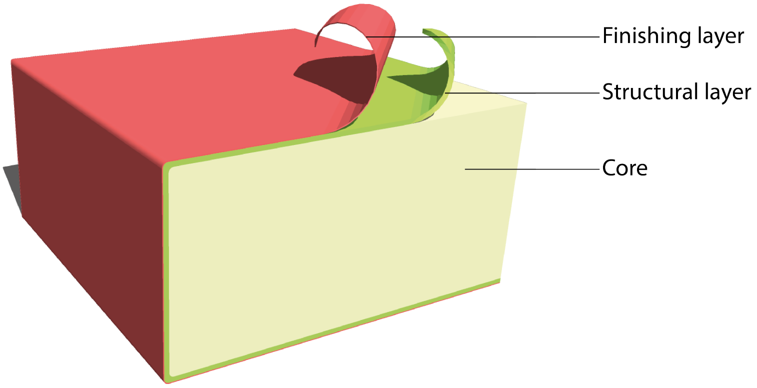

Figure 4.1: Partial visualisation of the structure of a self-bearing sandwich element

4.1.1 Core materials

The two main functions of the core layer are to serve as an insulator and as a spacer between the composite face layers. By enlarging the distance between the two structural layers of composite material, the flexural and shear rigidity of the entire element is increased. Transverse loading on the sandwich element, which is the most common type of loading on façades, is partially transferred by the core layer by means of shear. Therefore, the core layer needs to be a rigid foam with a very low density (ρ_c) of around 25 to 50 kg/m^3. It is possible to make use of foams with a higher density. The application of higher density foams for the core layer increases the stiffness of the sandwich element, but decreases the thermal resistance. The foam material for the core can be made of several different kinds of polymers, such as PIR (polyisocyanurate), PUR (polyurethane) and XPS (extruded polystyrene). Besides a subdivision in applicable polymers, namely thermoplastic and thermosetting, the main subdivision that can be made here is between open-cell foam and closed-cell foam. For structural applications, which is the case for FRP composite sandwich elements, it is preferred to use a closed-cell foam as core material. Open-cell foams are generally soft and easier to compress, closed-cell forms are harder and require a fair amount of loading in order to show significant distortion. Another advantage of closed-cell foams is that these foams have higher insulating values and show greater resistance against penetration and transport of water vapour. The downside of closed-cell foams is of course that they are generally more expensive than open-cell foams[39].

4.1.2 FRP composite materials

The first of two main ingredients of FRP composite materials is the polymer based resin. The main functions of the resin are to bind the fibrous material together, transfer the stresses from fibre to fibre, and protect the fibrous material from external influences. Similar to the polymers mentioned suitable for the core layer, the polymers applicable for FRP composites can be divided into two major groups, namely thermosetting and thermoplastic polymers. However, due to the high viscosity of thermoplastic polymers and the required high temperature and pressure during processing, thermoplastic polymer based resins are assumed to be unsuitable for this application, and will thus not be further discussed[2] [31].

Thermosetting resins can be divided into the following groups:

- Unsaturated polyester resin (UP)
- Vinyl ester resin (VE)
- Epoxy resin (EP)
- Phenol-formaldehyde or phenolic resin (PF)
- Polyurethane resin (PU)
- Bismaleimide resin (BMI)

Per group there are many different kinds of resin, all with a specific set of material properties. It is even possible to create resins based on a mix of polymers from different groups. Of these six groups UP resins are most often used in the building industry. This is mainly due to the low cost of the resin compared to the other available resins. Though, every resin group has its advantages and disadvantages concerning specific material properties such as strength, stiffness, impact resistance, thermal stability, moisture resistance and processability. The BMI group is the newest group of resins, and although this group of resins has generally the best overall performance of the resins mentioned above, these resins are very expensive. The resin is supplied with a mixed-in diluent and a cross-linking agent. The diluent decreases the viscosity of the resin for better fibre wetting and easier processing. The cross-linking agent causes the resin to become a solid after the reaction is activated by the catalyst. The catalyst is mixed through the resin prior to production, optionally with an accelerator and/or inhibitor in order to influence the gel-time of the resin, the duration that the resin keeps its fluid state after the addition of the catalyst. In most cases styrene is added to the resin, which serves as both diluent and cross-linking agent, making it a reactive diluent. Besides styrene there are many alternatives, which consequently provide the resin with different material properties. There are also a variety of additives that can be mixed through the resin. These are substances that improve specific material properties (mechanical or physical) or are added for aesthetical reasons. While these additives are added for a specific improvement, they may also have unwanted negative influences on other material properties. The mix of resin and additives combined is named matrix[3] [48].

The second main ingredient of FRP composites is the fibre reinforcement. The main function of the fibre reinforcement is to carry the external loading, but also to provide the necessary stiffness and thermal stability. The materials mostly used in FRP composites are carbon (or graphite), aramid (better known as Kevlar) and glass fibres. For every material there are different types of fibres available. A difference in composition of the fibrous material leads to an in- or decrease in strength and stiffness. Besides these synthetic fibres it is also possible to apply natural fibres. The foremost disadvantage of natural fibres is that the stiffness and strength of such fibrous material is significantly lower than that of the synthetic fibres.

The fibre reinforcement can be applied in FRP composites in different forms. There are three main forms of application available. Firstly, the fibres can be applied unidirectionally (UD) in the form of a tape or cloth, or by automated lay-up. Secondly, fibre reinforcement can be applied biaxial or multiaxial in the form of cloth and woven fabrics. And finally the last method is random fibre orientation, which is in the form of chopped strand mats (CSM), continuous filament mats (CFM), or manually or automatically applied by spray-up. The fibres are impregnated with a substance, the so called sizing, which functions as an adhesion promoter, and is crucial for a proper bonding between the fibre reinforcement and the matrix. The required sizing is dependent on the type of fibre material and the matrix composition[3] [31] [38].

It is of importance that the applied additives do not cause significant reduction to the adhesive and cohesive properties of the matrix and the sizing, since the matrix is the main responsible factor for the adhesive properties of the interfaces between the FRP composite layer and the core and finishing layer. Furthermore, the matrix and the sizing are responsible for the adhesive properties of the fibre-matrix interphase, which is the geometrical surface of the fibre-matrix contact layer, and the integrity of the FRP composite laminate as a whole.

4.1.3 Finishing layer materials

In principle two systems are available for the finishing layer on the composite material, namely a gelcoat and a lacquer coating. The difference between the two systems is as follows. The gelcoat needs to be applied in the mould before the fibre reinforcement is placed and impregnated with the matrix, while the lacquer coating is applied on the composite layer after it is cured and removed from the mould.

Gel coats are again a mix of multiple substances. It is composed of polymers, reactive monomers, pigments, fillers, thixotropic agents, promoters, inhibitors and other additives. The polymer used is mostly a polyester resin. The ones available are comprised of orthophthalic (Ortho), neopentyl glychol (NPG) and/or isophthalic (Iso) polyester resin. Besides polyester resin based gelcoats also epoxy based gelcoats are available. A coating of lacquer has the same function as the gelcoat, only the layer of lacquer is applied after the composite material is cured. The lacquer coating is similar to the gelcoat based on a thermosetting resin, for example polyurethane, and a mix of multiple additives with each its own function [4] [5].

The gelcoat needs to be compatible with the FRP composite material, especially with the matrix used in the FRP composite layer, since the finishing layer has to bond chemically with the matrix. In contrast to the gelcoat a lacquer coating relies on a mechanical bonding to the composite laminate instead of on a chemical bonding. The quality of a lacquer coating is mostly dependent on correct preparation and application of the finishing layer.

4.2 Material interaction with the production process

In this section production processes are discussed that mostly focus on the forming of a properly cured FRP composite laminate, although it is still of importance if it is possible to produce sandwich elements. Another point of attention here is the possibility of applying a gelcoat on one or both sides of the element. The applied materials, mostly the matrix of the FRP composite, and the production process show a lot of interaction, and consequently multiple demands and limitations are set by both sides.

There are several production methods available and each method imposes certain limitations on the material that is used. As for the limitations on the matrix set by the production method, these are mostly limited to the viscosity and gel-time of the matrix. Both of these properties are within limits influenced, desired or undesired, by additives. Of the general purpose thermosetting resins unsaturated polyesters have the lowest viscosities, vinyl ester, phenolic and epoxy resins have on average slightly higher viscosities. The viscosity of a matrix is, however, dependent on the type and the specific composition of the resin, and the type and amount of additives in the matrix. A general overview of the range of viscosities of both thermosetting and thermoplastic resins is shown in Figure 4.2 [6].

For open mould production methods, where the matrix is openly applied, these requirements only have a limited impact. Several methods, essentially all closed mould production processes, require the matrix to infiltrate the fibre reinforcement by flowing through a mould from one point to another. These methods require a matrix with rather specific material properties. Often, and especially in case of production methods with matrix infiltration, the requirements for the viscosity and gel-time of the matrix are also interdependent. For example, when the matrix has to cover a certain distance through the mould, this will go faster, and thus

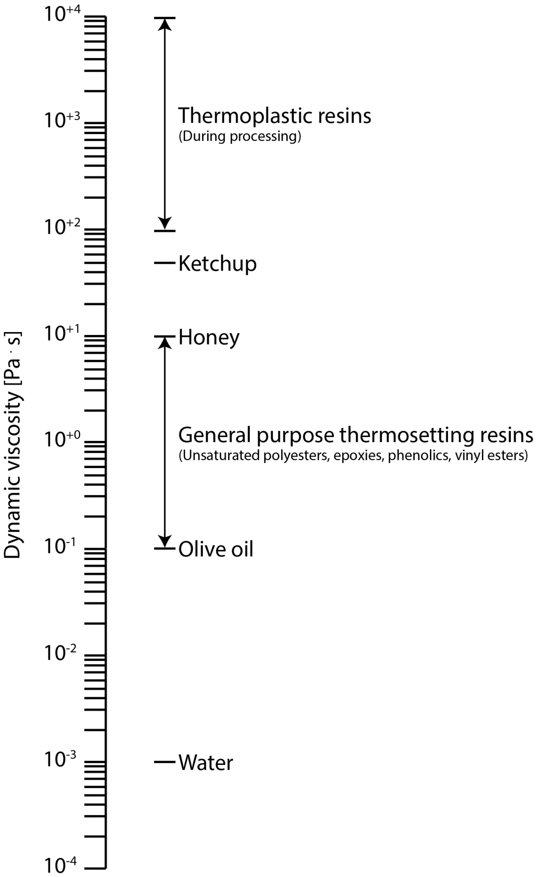

Figure 4.2: Range of viscosities of thermosetting resins in comparison with thermoplastic resins and various other fluids[6] [40]

will take less time, for a matrix with a low viscosity compared to a matrix with a higher viscosity. Therefore, the minimum required gel-time for the matrix with the low viscosity is then also lower than for the high viscosity matrix. It must be noted that the fibre reinforcement form, the fibre material and length, and the fibre orientation all influence the permeability and thus the speed of the flow of the matrix, and consequently the required gel-time of the matrix. An additional point of attention is that for matrices with a solid particle additive in combination with high volume fibre fractions in the mould, a certain degree of filtering of the particles will occur. Finally, the length of the fibre, the fibre orientation and the pressure difference between the in- and outlet of the matrix have an impact on the capillary effect, which influences the flow of the matrix and the saturation of the composite laminate. The higher the saturation is, the lower is the porosity of the composite laminate leading to a higher quality of the laminate[6].

Not all materials can be used in combination with all production processes. A large part of the available matrices only cure properly under heightened temperatures, and in some cases also under pressure. Only a number of unsaturated polyester, vinyl ester and phenolic resin based matrices, and a few epoxy resin based matrices can cure properly with little to no application of heat. For civil engineering purposes rare cases may even require a post-cure process. Resins that only cure properly under heightened temperatures require a hot mould system, which can be both an open and closed mould system. Curing and post-curing under heightened temperatures and pressure requires an oven or autoclave. During the curing of the matrix the polymers form a cross-linked network, which gives the matrix its stiffness and strength. The requirement of applying heat and pressure during the curing process does significantly increase the overall costs of the production process, but may also decrease the production cycle time. The application of heat triggers the cross-linking of the matrix and/or speeds up this curing process. However, the formation of cross-links is a never-ending process and is actually one of the main causes of ageing of the matrix. The continuous formation of cross-links reduces the elasticity of the matrix, and thus the composite material, and makes it harder and more brittle. There is also a major upside to curing the composite under heightened temperatures and also the ageing process. The formation of cross-links increases the glass transition temperature (T_g) of the composite and therefore the maximum continuous-use temperature of the element. Finally, the material properties after cure are not only determined by the production process itself, but also by the handling of the matrix and fibrous material before and during production of the element. The presence of impurities, insufficient mixing of the matrix, wrongly applied ratios and air entrapment in the composite laminate can cause the final product to be less durable[3] [14] [15] [16] [31].

There is some flexibility in the combination of the production process and the materials used for the FRP composite sandwich element. For the application of a gelcoat on both sides a closed mould system is required. Nevertheless, in the cases the production method does not allow for the application of a gelcoat it is of course always possible to provide the composite laminate with a protective finishing layer of lacquer.

One thing that must be taken into account is the size of the mould. Most matrices show shrinkage during the curing process. The amount of shrinkage depends on the type and composition of the matrix and the fibre volume fraction and fibre reinforcement form, principally on the entire composite laminate design. Once a mould has been made for a specific FRP composite, the resulting product from this mould will be different when the applied materials for the end-product change[30] [31].

4.3 Critical components and material connections

In principle the critical components, the anchor construction, windows and sealing, as are visualised in Figure 1.2, are attached to the sandwich element after the sandwich element is removed from the mould. During the design of the FRP composite sandwich element the manner of connecting the components to the sandwich elements is generally a complex process and requires a lot of attention. In this chapter four applicable methods of connecting these components are assessed. The critical components can be clamped, glued or screwed onto the sandwich element, or mounted via a bolted connection with an in the sandwich element integrated plate or bracket. All types of connections behave differently interacting with the FRP composite material.

4.3.1 Clamped connections

Firstly a component can be connected to the composite sandwich element by securing it clamped around a protrusion or in a crevice. Simplified examples of such a connection are shown in Figure 4.3. These kind of connections require the mould of the sandwich element to be somewhat more complex, especially in case of the presence of a crevice.

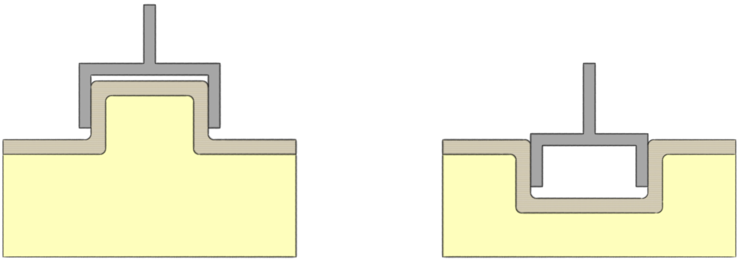

Figure 4.3: Simplified visualisations of clamped connections

A clamped connection can only be used in the same plane as the sandwich element, since it is kept in place by surrounding the sandwich element, or by being surrounded by the sandwich element. Principally, the space between the metal profile and the FRP composite sandwich element is filled with a rubber seal, which provides friction and transfers the loads, and also creates a weather-tight seal. Such connections can therefore be applied for the seal around the sandwich element and for window frames. It must be taken into consideration that the composite material is susceptible to expansion due to temperature differences. The clamped connection must therefore be able to handle the resulting contraction, expansion and other deformations.

4.3.2 Glued connections

A second option is to structurally glue the component onto the sandwich element. Here it is of importance that the adhesive strength of the glue on the finishing layer, gelcoat of lacquer coating, and the adhesive strength between the finishing layer and the composite laminate are sufficient. These factors, and the climatic conditions during fabrication and in service all have an influence on the quality, the final strength and the rate of deterioration of the connection during use[7] [31].

A glued connection between two FRP composite components can take many shapes. The components can be connected directly with for example a single lap joint, butt joint or scarf joint, or with an additional piece of material creating a single or double strap joint. Since the monolithic sandwich elements are completely enwrapped with the composite laminate, there are no ends of the laminate present in the element. Therefore, only single lap joints are applicable, of which two simplified examples are shown in Figure 4.4.

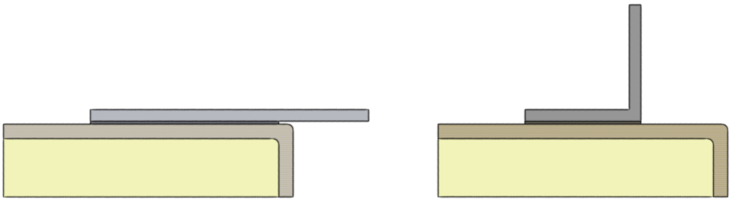

Figure 4.4: Simplified representations of single lap joints[31]

The adhesive layer performs best as it is subject to in-plane shear and out-of-plane compressive loading. Wrongly designed connections or deformations of one or more of the connected components may cause excessive local tensile stresses, the so called peel stresses, to which glued connections are much less resistant. This is visualised in Figure 4.5. The consequential fracturing in the glued connection is also indicated in this figure[31].

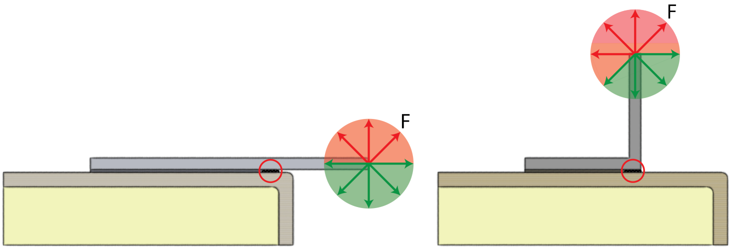

Figure 4.5: Direction of the load F on a to the sandwich element glued component that will (red area) or will not (green area) cause peel stresses in the glued connection

4.3.3 Connections with fasteners

The third and fourth method concern connecting the components by using fasteners. These two methods comprise a connection made with screws that are anchored directly in the composite laminate, and a bolted connection where the external component is fixed to an in the sandwich element integrated plate or bracket. A simplification of both methods is shown in Figure 4.6. As the screwed connection relies on a direct transfer of forces from the screws to the composite laminate, thereby causing high local stress concentrations, the bolted connection spreads the forces over a larger surface area via the integrated metal plate. The bond between the integrated plate or bracket that ensures this behaviour is often referred to as a chemical bond, as the connection between the composite laminate and the metal component is made during the impregnation of the fibrous material, without the application of any additional adhesive[48].

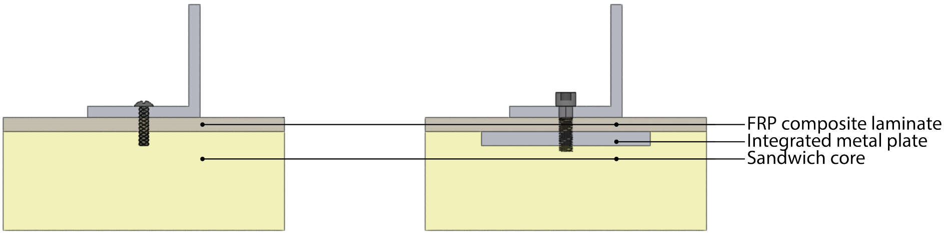

Figure 4.6: Simplified visualisation of a screwed connection (left) and a bolted connection (right) in an FRP composite sandwich element

Connections with fasteners rarely consist of a single bolt or screw. Both the number of rows in a joint with fasteners as the materials of the two components that are joint together with this connection influence the distribution of the shear loads in the fasteners. The distribution is shown in Table 4.1. Here it must be noted that these values represent the load transferring to fasteners in series. Furthermore, the design of the laminate has a major influence on the integrity of the laminate and thus on the ultimate strength of a bolted or screwed joint.

Combining a glued connection with a screwed or bolted connection combines the advantages of both connections and minimises for a large part the disadvantages of both types of connections. This is applicable for both the connection with an integrated plate or bracket, and an external component connected directly on the composite laminate. With the application of such connections the concentration of stresses near the holes for the fasteners is reduced. Also failure due to tension and shear-out is in this case reduced. Though the overall strength of a combined connection is not equal to the sum of each of the connections separately. Furthermore, it is of importance to pay attention to the path of the transferred stresses. Glued and combined connections transfer stresses best via in-plane shear and compression. It is advisable to limit or completely avoid other methods of transferring

Table 4.1: Fastener load distribution in single and multiple row joint (as proportion of average fastener load) [8]

Number of rows		Row 1	Row 2	Row 3	Row 4
1	glass FRP / glass FRP	1.00	-	-	-
	glass FRP / metal	1.00	-	-	-
2	glass FRP / glass FRP	1.00	1.00	-	-
	glass FRP / metal	1.15	0.85	-	-
3	glass FRP / glass FRP	1.10	0.80	1.10	-
	glass FRP / metal	1.50	0.85	0.65	-
4	glass FRP / glass FRP	1.20	0.80	0.80	1.20
	glass FRP / metal	1.70	1.00	0.70	0.60
> 4	Not recommended				

Note: In the glass FRP/metal joint, Row 1 is the row nearest the end of the glass FRP member

stresses. When tensile stresses or bending moments are transferred from the FRP composite laminate to the component, or the other way around, high peel stresses and pulling through of the fasteners can occur transverse to the plane of the composite laminate. In some cases pulling through of fasteners can be avoided by applying (larger) washers [9] [10].

4.3.4 General behaviour of connections in combination with FRP composites

Both glued and bolted or screwed connections between FRP composite laminates or between a metal component and an FRP composite laminate show different behaviour. Glued connections have the tendency to fail without any warning and therefore need a lot of attention.

Screwed and bolted connections have a large negative impact on the fatigue behaviour of the composite laminate due to the concentration of stresses alongside the hole in the composite laminate. This same hole also influences the integrity of the laminate. Cutting holes in the composite laminate interrupts the continuous fibre reinforcement in the laminate. Creation of the holes must be done with the right tooling and with diligence and precision. Drilling or cutting of the hole after the curing process of the composite laminate can create additional damage to the laminate in the form of local fracturing and delamination. Furthermore, around the edges of the hole arise stress concentration as the sandwich element is loaded. These factors all reduce the overall strength of the laminate and the connection to a significantly higher degree than would be the case for a connection with fasteners between two metal components. Nevertheless, real-life testing is required in order to determine the strength of the screwed or bolted connection in the applicable directionalities. Hereby it should be assumed that the screw only grips in the composite laminate, not in the core material[7].

Besides physical testing it is rather difficult to make an accurate prediction of the strength and the mode of failure of a connection involving composite materials, since the governing failure mode of the connection is dependent on the combination of the FRP composite composition, the placement of the fasteners, the fibre reinforcement form and orientation, and the thickness of the laminate. The different kind of failure modes are shown in Figure 4.7. However, FRP composite is not a ductile material. High local stresses near the fasteners do not make the composite laminate to yield. As soon as the limit of the material is reached it will break. Considering the influences of the composition of the laminate, a composite laminate with a semi-isotropic lay-up, existing of 25 % of the reinforcement in all directions ⟨-45 °,0 °,45 °,90 °⟩, provides the best integrity near connections with fasteners. Other laminate compositions may show failure due to tension or shear-out at lower stresses. Leaving the composition of the composite laminate aside, it is advised that the distance between the centroids of the fasteners, or the distance between the centroid of the fastener and the edge of the laminate is four times the diameter of the fastener in order to obtain the optimal connection strength. Failure modes and causes, and fracture patterns are further discussed in the third part of this thesis[7] [8] [31].

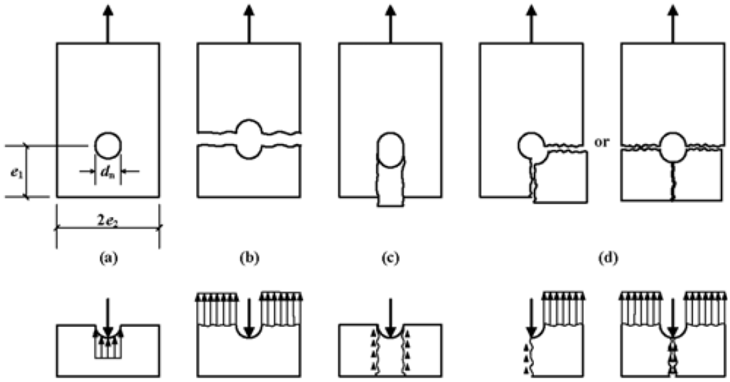

Figure 4.7: Plate-to-plate distinct modes of failure with a single steel bolt; (a) bearing, (b) net-tension, (c) shear-out, (d) cleavage[18]

For all connections it must be taken into account that the FRP composite laminate is visco-elastic. Long-term stresses cause the composite to creep and long-term deformation causes composite material to relax. Some ways to deal with this kind of material behaviour is discussed in Section 4.5. An additional consideration concerning connections with fasteners in an FRP composite laminate with carbon reinforcement is that this composite material may cause galvanic corrosion in the fastener. In this case the fasteners need to be coated in a non-conductive coating[31].

4.4 Technical specifications for materials and material properties

The technical specifications are mostly applicable for the functioning of elements and structures as a whole. Generally the specifications cover the static and thermal behaviour, long term durability, aesthetics and the fire behaviour of the element. Other specifications or requirements are considered special and are not discussed here.

4.4.1 Static behaviour

Considering static behaviour, or mechanical behaviour, part of the specifications is directly applicable to the material properties of the applied materials. Structural specifications and requirements are principally pre-set by national and international legislation. In the Netherlands this is a combination of European standards and national appendices. These specifications focus on the structural strength, stiffness and stability of structural elements and structures. There are standards available for certain materials and for sandwich elements, containing information such as applicable material factors and analytical calculation methods. However, there are not any standards available for FRP composites and FRP composite sandwich elements. There are generally accepted guidelines that do prescribe such information. In the Netherlands this is CUR 96, although internationally (Europe) Eurocomp Design Code and Handbook is the accepted guideline for FRP composite elements. It must be noted that in both guidelines mentioned above it is assumed that the fibre reinforcement is made of glass fibres.

4.4.2 Thermal behaviour

As for the thermal behaviour of these elements, there are two specifications of importance. The first one is the glass transition temperature (T_g). This is a material property of the FRP composite and indicates up to which temperatures the element can be used. CUR 96 amongst others recommends that the value of the T_g of the FRP composite material is at least 30 °C higher than the maximum continuous-use temperature. The maximum continuous-use temperature is dependent of the applied colour and is set by national or international standards. For the Netherlands this is 50 °C for bright light colours, such as white or crème, 60 °C for light colours, beige, green or light blue, and 75 °C for dark colours, as is set in NEN-EN 1991-1-5. Of the thermosetting resins epoxies and especially bismaleimide resins have the highest $T_{(g)}$ [31] [35].

The other thermal behaviour of the façade element that is of importance is its deflection due to temperature differences between the inside and outside environment. Dependent on the specific composition of the FRP composite material the coefficient of thermal expansion (CTE) is equal or higher than the CTE of metals that are normally used to construct the façade elements. Therefore, the transverse deflection of the façade element due to temperature differences, might cause problems and exceed the maximum value, in particular as the façade elements become larger. The characteristic maximum and minimum temperatures during service, that are required for the necessary calculations, are also dependent on national or international legislation, for the Netherlands this is described in the standard NEN-EN 1991-1-5[35].

4.4.3 Durability

Another important set of properties of the applied materials, especially of the FRP composite, is the long term or time dependent behaviour of the materials, in other words the durability of the materials. In the structural calculations this is often described with a material factor, which decreases the mechanical properties in order to account for the degradation of the material in the long run. Since the matrix shows visco-elastic behaviour, the FRP composite material as a whole is subject to creep and relaxation. Façade elements are also exposed to weather influences. Therefore, the façade elements may show fatigue induced degradation due to dynamic wind loads and thermohygral degradation. The fibrous material principally does not show any significant forms of creep and relaxation, but does show degradation caused by fatigue. The fatigue strength of the fibrous material increases with the modulus of elasticity, high modulus materials have a very slow reduction in strength and stiffness. For example E-glass fibres, which is the most commonly used fibre reinforcement material used in civil engineering structures, show a fatigue strength reduction of about 8 % to 12 % per decade. Though it must be noted, and as is mentioned earlier, that these values are only indicative as there is a lack of documentation on long term degradation of FRP composite materials for civil engineering applications. This concerns especially the magnitude of the effects of creep and dynamic loading on the interphase between the fibre reinforcement and the matrix. In the guidelines this problem is solved by applying a material factor, which is often based on conservative values and/or values from other industries[16].

What is known though is that the behaviour and degradation of the material due to creep and fatigue is for a large part dependent on the design of the FRP composite laminate. This is further discussed in the next section. Thermohygral degradation is dependent on the outside environment and is discussed in a later stage of the analysis in Section 4.6.

The previously mentioned guidelines each consider the influences of long term behaviour of composite materials. In CUR 96 this is taken into account in the conversion factor, the material factor in this guideline is dependent on the applied production process. The conversion factor is build up of four elements, which describe the influence of temperature, moisture, creep and fatigue. The partial conversion factors for temperature, moisture and fatigue are for all composite laminate compositions the same, although the partial conversion factor for moisture is dependent of the climate the composite containing element is located in during service. The partial conversion factor for creep is dependent on the form of the fibre reinforcement. Here it is assumed that the lowest amount of creep occurs with unidirectional fibre reinforcement (along the fibre direction) and the highest amount of creep with random oriented fibre reinforcement. These factors take into account that with random oriented fibre reinforcement the maximum achievable fibre volume fraction is significantly lower than with unidirectional fibre reinforcement[33].

The BÜV-Empfehlung, the German equivalent of CUR 96, works with a partial safety factor (γ_M) and material specific modification factor A_{mod}. Here the partial safety factor is dependent on the limit state. The partial safety factor is 1.0 or 1.1 in the serviceability limit state, and can be determined from a table in the guideline for the ultimate limit state, where it is dependent on the type and location of loading, and the material composition. The modification factor is a product of three partial factors. These partial factors describe the influence of the duration of the loading, the environmental influences, and the influence of the ambient temperature during use. All partial factors are furthermore dependent on the precise composition of the composite laminate and can be determined from tables in the guideline[34].

The Eurocomp design code makes also use of a partial safety factor (γ_{M}). Though in this guideline the partial safety factor is composed of a product of three partial factors describing the material properties from test values, the material and production process, and environmental effects and duration of the loading on the composite material. The minimum and maximum values of these partial factors are predetermined in the guideline[8].

4.4.4 Building physics

Requirements concerning the building physics mostly concern the thermal resistance and weather-tightness of the façade, but also the prevention of cold bridges and protection against noise from outside. As for the weather-tightness this is mostly dependent on the sealing in between the façade elements and the connection between the critical components and the FRP composite sandwich element. The composite laminate itself also needs to be weather-tight to prevent the ingress of water into the sandwich element. However, this is not of significant importance for the building physics, but is applicable to the interaction between the materials and the environmental influences, and will therefore be discussed in that specific section. The minimum requirements for the thermal resistance are generally enforced by national legislation. In the Netherlands the minimum thermal resistance is set by the Dutch Building Decree and has currently a value of $R_\mathrm{c} = 3.5\ \mathrm{m^2K/W}$, although clients may demand higher values[36].

Principally the thermal insulation of the sandwich element is provided by the core. However, the core is completely wrapped with FRP composite material. This means that, dependent on the thermal conductivity of the material, the composite laminate can cause cold bridges around the edges of the element. The thermal conductivity of the composite laminate is determined by the thermal conductivity of the matrix and fibres, the interaction between the matrix and the fibres, and the fibre orientation. The thermal conductivity of epoxy and polyester based resins is generally around $\lambda = 0.17\ W/(mK)$. The thermal conductivity for glass ($\lambda = 1.00\ W/(mK)$) and aramid ($\lambda = 0.04\ W/(mK)$) can be considered the same for both the fibre direction as transverse to the fibre. For FRP composites with either of these two fibrous materials the thermal conductivity can be determined easily by taking the average thermal conductivity dependent on the volume fractions, though this is a simplified method. This method is not entirely usable for composites with carbon fibre reinforcement, as the thermal conductivity along the fibre direction is much higher than perpendicular to the fibre direction. Carbon fibre has a moderate to very high thermal conductivity in the fibre direction, which generally is between 8 and 1000 $W/(mK)$. Even though it depends on the carbon type applied, composite laminates with carbon fibre reinforcement have a relative high chance of causing cold bridges in the sandwich element[11] [12] [13].

The required protection against noise from outside is dependent on the local situation and on the corresponding national legislation. The protection that the façade element offers is only in small quantities dependent on the materials used for the sandwich element. The design of the element, mostly the thickness, and the critical components have a larger influence. Since this is different for every situation there will not be paid close attention to this requirement and the corresponding material properties.

4.4.5 Fire behaviour

One of the requirements that relates to the behaviour of the applied materials are the requirements related to the material behaviour during fire and the accompanying smoke production. The ignition temperature (T_{ig}) of composite materials is quite low, generally between 250 – 400 °C. As the composite material decomposes, principally the matrix for the most part, it releases hydrocarbon gasses, which are an excellent fuel for the fire. Dependent on the resin and additives the matrix in the structural and finishing layer is composed of, also smoke and toxic gasses can be released during combustion. Smoke and toxins are generally more dangerous than the flames and heat. Translating the requirements concerning fire behaviour into regulations applicable in the Netherlands, in the Dutch Building Decree the lowest requirement for façade elements is fire class D. However, as most buildings with unitised façade elements have a total height of more than thirteen meter, the required fire class is increased to fire class B for the exterior surface area of the element. The interior surface area of the façade elements are required to comply with the same fire class as the exterior surface area in combination with the additional requirement of smoke class S2. The fire and smoke classes of the façade elements need to be determined according to European standard NEN-EN 13501-1. It must be noted that in the Dutch Building Decree and the European standard currently no quantifiable requirements are made concerning the release of toxic gasses in case of fire, which may be a concern in case of burning polymer based materials[16] [36].

As is mentioned above, of the ingredients of FRP composites the resin in the finishing and structural layer is the flammable material, which, partially dependent on the additives, may also produce a large amount of (toxic) smoke when it burns. As the fibre volume fraction is smaller, the flammability of the composite material becomes greater. Most composite materials can reach fire class D without altering the composition of the matrix. However, in a fire the largest part of the matrix serves as fuel for the fire and will burn up most of its mass. In order to reach fire class B with smoke class S2 the most matrices need additives. These additives will reduce the flammability of the matrix material by releasing water vapour, adding intumescent behaviour, increasing char-forming, or a combination of these reactions. Due to their natural char-forming ability phenolic and bismaleimide based matrices are better equipped against fire in comparison to polyester, epoxy and vinyl ester based matrices, and may reach fire class B and smoke class S2 without any additives[16].

One of the traditional ways to improve the fire behaviour of composites is to add certain fillers to the matrix. On the one hand these fillers dilute the flammable material, and on the other hand they possess intumescent, char-forming and/or water vapour releasing properties. Applicable fillers are aluminium hydroxide (ATH), magnesium hydroxide (MDH), boron based fillers, such as boric acids, borax or zinc borate, antimony based filler, such as antimony oxide, and phosphorus based fillers, such as phosphate esters, phosphonates and phosphinates. Most of the fillers act as a flame retardant, fillers that contain zinc also act as a smoke retardant. The most used filler is ATH due to its intumescent behaviour, release of water vapour and its low cost. The downside of these fillers are the amounts of filler that are required in polyester, epoxy and vinyl ester based matrices in order to get the required result. The matrix consists on average 50 % to 60 % of its weight out of these fillers. Additionally the aforementioned fillers are known to have a negative influence on the mechanical properties of the matrix, and also on the adhesive and cohesive properties of the matrix, creating a low performing and brittle composite laminate. Furthermore, these fillers increase the viscosity of the matrix reducing the processability of the matrix[14] [16] [27] [37].

Another traditional method of increasing the fire resistance of the composite material is to make use of halogenated resins. In this case the polymers are chemically altered by adding halogen compounds, often containing chlorine or bromine. As the matrix decomposes in a fire, the reactive halogen species are released and terminate combustion reactions, reducing the extent of the fire. However, halogenated resins have a major downside. During fire these resins release corrosive, acidic and toxic gasses, amongst which hydrogen halide, that are formed during combustion[16] [27].

The methods for improving the overall fire behaviour of the composite material that are mentioned above have some major downsides, which consequently have encouraged research for alternatives. Currently there are two upcoming trends. The first trend is adding fillers consisting of nano particles. Nano particles that have shown positive results are carbon nanotubes and nano particles based on the mineral montmorillonite. The last set of nano particles are often called nanoclay. The addition of nano particles to the matrix, instead of the traditional fillers, comes with a large amount of positive effects. Initial research shows that the fire behaviour of the composite material is improved by an increased ignition time, a reduced peak heat release rate and increased char-forming. This is even noticeable at very low weight percentages of 3 % – 5 %. The addition of nano particles also shows a similar or greater stiffness and strength of the matrix compared to the same matrix without any nano fillers, and also an increased thermal stability. Furthermore, the addition of nano particles shows minimal changes in the viscosity of the matrix. In case of the nano clay, the effects of the addition of the nanoclay on the different material properties is dependent on the specific composition of the nanoclay. These nano particles are natural occurring minerals which are mined from several places spread over the globe, mostly in the United States of America and China. Every mine supplies a different nanoclay, and consequently the processing of the minerals also have an influence on the composition of the nano particles[16] [22] [24] [28].

The second trend is a type of chemically altering the polymer molecules named graft co-polymerisation. This technique involves attaching monomers to the polymer, which have high char-forming characteristics. Monomers suitable for this application are alkaline earth salts, alkali metal salts and salts consisting of methacrylic and acrylic acids[16].

All fire behaviour improving methods discussed above assume that the entire façade element, or at least the FRP composite part, needs to be sufficiently fire resistant. They also all require the matrix to be modified. An alternative for this is to shield the FRP composite part from fire, so that the composite laminate only has to fulfil a structural function. This would mean that the finishing layer is required to be sufficiently fire resisting in order to protect the structural layer, besides having an aesthetical function. A second option is to apply an additional layer between the finishing layer and the structural composite laminate. In both cases the fire barrier can protect the composite substrate in one of three different ways, namely as a flame retardant, a thermal barrier or by intumescence. Flame retardants exist of fire resistant organic polymers, such as brominated polymers, or of inorganic materials, for example geopolymers. Organic flame retardants release volatiles at elevated temperatures that react with H• and OH• radicals, which otherwise would fuel the combustion process, thereby preventing the radicals to contribute to the fire. However, similar to the halogenated resins, organic flame retardants also release toxic gasses. Inorganic flame retardants protect the composite substrate by slowing down the heat conduction due to its low thermal conductivity, and its high thermal stability, which can reach values higher than 1000 °C. Thermal barriers can be formed by applying an additional layer between the finishing layer and the composite laminate with ceramic fibrous mats, based on silica or rockwool, or ceramic plasma sprayed films, based on zirconia or aluminium. The application of an intermediate thermal barrier may cause problems with the integrity of the façade element between the finishing layer and the thermal barrier, and/or the thermal barrier and the composite laminate. The third way of protecting the composite laminate is by forming an intumescent and/or char-forming barrier. Fire retardant gelcoats and lacquers are generally filled with intumescent and/or char-forming additives, mostly the same fillers as are used to improve the fire behaviour of the FRP composite material. These fillers have consequently the same up- and downsides in the gelcoat or lacquer coating as is mentioned above when these fillers are added to the matrix. Again, similar to the thermal barrier it may be required that steps are taken to guarantee proper adhesion between the coating and the composite substrate and that the finishing layer still properly protects the composite material against the elements[16] [23].

4.5 Influences of the element and material design

The materials used in an FRP composite sandwich element do not have a lot of influence on the shape and design of the element itself. The element can principally take any shape. However, any limitations can be set by the production method with which the element is produced, which is discussed later on. On the other hand, the design of the composite laminate has a significant impact on the performance of the composite material. For a large part the laminate is designed to make the entire element strong and stiff enough at the locations and in the right direction this is required, thereby creating a fibre reinforcement that can be different for all surface areas of the element. The type and the orientation of the fibre reinforcement in the laminate, as mentioned before, also have a significant influence on the time-dependent behaviour of the composite laminate and thus on the entire element. This should be taken into account during the design of the element.

The first property of the FRP laminate that is discussed is its visco-elastic nature due to the matrix, and the accompanying creep and relaxation behaviour. Degradation of the composite material due to creep and stress relaxation principally only occurs under sustained loads over a long period in the order of multiple years. For façade elements this means that this mode of degradation can only be induced by the self-weight of the element and of the components mounted to the element. FRP composite with glass or carbon reinforcement show normally very little creep at normal indoor temperatures, around 20 °C, although this is influenced by the orientation of the fibres and the fibre volume fraction. The maximum creep strength reachable is around 90 % of the ultimate strength with unidirectional fibre reinforced composite laminates, where the fibres are oriented in the direction of the stress. Composite material is most susceptible to creep when the stresses are perpendicular to the orientation of the fibre. Generally it is assumed that FRP composite laminates do not fail due to creep- and stress-rupture, as long as under sustained loads the stresses in the laminate do not exceed 25 % to 30 % of its ultimate capacity[16] [29] [31].

Creep and stress relaxation of composites in service is also strongly dependent of the state of cure of the material. The creep behaviour of composites becomes more significant as the composite has completed a smaller part of the curing process. Moisture absorption and increased continuous-use temperatures also increase the significance of the composites creep susceptibility. However, as the composite material ages it continues to create cross-links, consequently increasing its resistance against creep and relaxation[16].

Façade elements are subjected to dynamic or variable loads, mostly due to wind, but temperature difference and the resulting deformation of the element also plays a role, and is therefore susceptible to fatigue induced failure. For the FRP composite sandwich elements this is for the most part applicable to the composite skin. The continuous change in deformation causes the composite material to have a progressive reduction in stiffness, characterised by debonding of the fibres that are oriented perpendicular to the stress, breakage of the fibres and the forming of micro-cracks in the matrix. The formation of micro-cracks is the most common occurrence, of which the propagation over a longer period is mostly determined by the thickness of the lamina, which contains the fibres that are oriented perpendicular to the stress, in other words the 90°–lamina or 90°–ply. For thick plies the propagation is generally instantaneous, but for very thin plies the propagation of such cracks can be even suppressed. This is applicable for both static loading, due to self-weight, and for variable loading, due to wind and temperature differences[14] [16] [25].

The fibre type, orientation and also the lay-up scheme of the entire composite laminate have a major influence on the fatigue performance of the FRP composite laminate. As is mentioned earlier, fibre material with a higher modulus has a higher fatigue resistance. Besides the material itself, the directionality of the majority of the fibre reinforcement has a strong influence on the fatigue resistance. Most of the resulting damage occurs alongside fibres that are not oriented in the direction of the stress. Also an increase in quantity of off-axis fibres decreases the fatigue resistance of the composite laminate. However, tests have shown that alternating laminae with ±5° relative to the directionality of the stress increases the fatigue strength. Also the addition of a small percentage of 90°-oriented fibres reduces the tendency of splitting between the fibres that are oriented in the direction of the stress. Both cases improve the general integrity of the composite laminate[16].

In the long run degradation due to fatigue, especially the formation of micro-cracks, amplifies the effect of creep, and the other way around. Both fatigue and creep are making the FRP composite more susceptible to environmental influences, and consequently these environmental influences degrade the composite material at an increased rate, making it more susceptible to creep and less fatigue resistant. The deterioration of the composite material leads in the long run to an accumulation of micro-cracks up to macroscopic cracks, debonding between the fibres and the matrix, delamination and fibre fracture[29].

Both the best fatigue and creep performance result from orienting the majority of the fibre reinforcement in the direction of the stress, with a small amount of reinforcement perpendicular to the directionality of the stress to ensure the integrity of the composite laminate. However, the creep inducing stress and the fatigue inducing stress are not necessarily in the same direction. Such cases require a balanced laminated dependent on the relative stress values and the natural fatigue and creep resistance of the matrix and fibre material, reducing the possibility of fatigue- or creep-induced failure of the element during its service life[16] [29].

4.6 Interaction between materials and environment

The interaction between the materials used for the FRP composite sandwich element and the environment can be easily set out over the entire life-cycle of the element. In the first place the choice in materials has a certain impact on the environment. The fibre and matrix material need to be mined and/or produced, refined and processed until they are suitable for the production of the composite element. The parts of this, which in the end can be quantified, are the embodied energy, CO_2 footprint and the water usage for the materials. The same is applicable for these properties of the subsequent production processes regarding the sandwich elements. In the second stage, the period that the element is in use, the environment has a specific influence on the element. Temperature, moisture, UV radiation, all these factors have in a greater or lesser extend a degrading effect on the façade elements. In the last stage of the life-cycle, the elements have to be recycled. During this stage the sandwich elements are again a burden on the environment. The degree of this, however, is dependent on the materials used and the recycling technology that is available. In the following sections these stages are discussed in more detail.

4.6.1 Procurement, processing and recycling of the materials

The gelcoat or lacquer coating, the matrix in the FRP composite, and the core material are generally all based on specific polymers, which in the most cases have an origin as a petrochemical by-product. The refinement process and the accompanying energy required differ per polymer. Since the polymers are based on fossil fuels, they do have a significant impact on the environment when is looked at their procurement.

Energy required for the primary production of thermosetting resins, or thermosets, meaning the mining and refining process of the polymer compounds, is for the different types of resins quite similar. For example, 85 – 95 MJ/kg is required for the primary production of a polyester or phenolic resin, and 105 – 130 MJ/kg for epoxy resins. The CO_2 footprint for these resin types show a similar trend. Polyester and phenolic resins have a CO_2 footprint of around 3 kg/kg, epoxy resins just over 4 kg/kg. Additionally, the embodied energy of materials that can be used as fibre reinforcement shows much larger disparities. E-glass fibre has an embodied energy of just over 50 MJ/kg, but for carbon fibre this is more than 200 MJ/kg. The differences between these materials origin for the largest part from the different production processes that are necessary to manufacture the fibrous materials. It must be noted that the higher mechanical properties of carbon fibre do not outweigh the amount of energy that is required for production when compared to glass fibre. Comparing these values to steel and aluminium, the values concerning embodied energy and CO_2 footprint for steel are similar to those of the resins, but are for aluminium significantly higher. Aluminium has an embodied energy of 200 – 240 MJ/kg and a CO_2 footprint of 11 – 13 kg/kg. Comparing the entire procurement and production process of FRP composite structures with similar structures executed in these metals, FRP composites have a significant lower embodied energy and CO_2 footprint, caused by the lower density of composite materials. Since rigid foams are generally also made of thermosetting resins the embodied energy and CO_2 footprint show similar values compared to the aforementioned resins. What is striking is the amount of water that is required for the production of the polymeric compounds. Values of 90 – 215 l/kg water usage for the primary production of resins is common. For the production of rigid foams this can even reach values up to 865 l/kg. For the primary production of steel the water usage amounts to 23 – 69 l/kg, for aluminium 125 – 375 l/kg[42] [49] [50].

Due to the bespoke nature of façade elements, and also the inaccuracy of determining a reliable degree of degradation of the elements due to physical and thermal ageing, it is unlikely that these elements can be reused as a whole. Assessing the materials used for the production of these elements, the polymer-based materials used are generally all thermosets, including the core material, and the main downside of thermosets in comparison to thermoplastics is that these polymers cannot be melted down and reshaped yet. This makes that it is principally not possible to reuse such polymer based materials for the same service level. It is, however, possible to make pallets for injection moulding or regrind the materials into flakes for compression moulding. This kind of recycling is second category recycling, since the material is reprocessed into a degraded service, or in other words downgraded.

Another option is to incinerate the polymer-containing parts of the used elements. FRP composites and the polymeric core generally have a high calorific value, which can provide energy recovery via incineration. However, it must be taken into account that depending on the composition a large amount of toxic gasses can be released during this process [31] [42].

With an eye on reducing the environmental impact of composite materials, upcoming trends are the application of natural fibres in synthetic resins, which are then called eco-composites, and the application of biodegradable resins. Hemp, flax, linen and cotton fibres are some of the many available types of natural fibre that can be used in such composite materials. For structural applications natural fibres have a couple of major downsides, of which the most important one is that natural fibres can only be used in short fibre reinforcement form. This means that UD or any other form of continuous fibre reinforcement with natural fibres is precluded. Furthermore, the mechanical properties of natural fibres are in most cases two or more times lower than of glass fibre. Biodegradable resins have become only recently available, both in thermoplastic and thermosetting form. Due to the novelty of these resins the products that are available lack the processing and performance characteristics that the general purpose synthetic resins have, such as unsaturated polyester and epoxy [42] [44].

4.6.2 Environmental influences on the materials

The façade elements endure on the interior side a reasonably stable climate, meaning room temperature and normally a relative humidity between 40 % and 60 %. On the exterior side the element is subjected to the local weather influences, of which most have a degrading effect. Of all used materials the finishing layer has the most interaction with the elements. The finishing layer is subjected to UV radiation and is the only part of the FRP composite sandwich element that can be in direct contact with moisture and hazardous substances. Therefore, the main objective of the finishing layer is to protect the underlying composite laminate from all this, besides taking care of the aesthetics of the element. Dependent on the composition of the finishing layer it can also have the function of protecting the composite laminate and core material against fire, but this is already discussed in Section 4.4.

Firstly, the degrading effects of UV radiation, also called photo-degradation, are discussed. This type of degradation is only applicable for the finishing layer since UV radiation penetrates at most a couple of micrometres of the surface. UV radiation is divided into UVB radiation, of which the wavelength is between 280 and 315 nm, and UVA radiation, with wavelengths between 315 and 400 nm. UV radiation with lower wavelengths indicates higher photon energies and has consequently a higher impact in the degradation process of polymeric compounds. Several thermosetting polymers are known to be affected by radiation with wavelengths in the range of 295 to 400 nm. However, the magnitude of the impact on the finishing layer differs per type of polymer and the precise composition of the gelcoat or lacquer coating. The consequences of photo-degradation are numerous. The least severe ones are loss of surface gloss, surface discolouration and chalking. Although, from an aesthetic point of view this is already quite serious. Elements with light colours tend to show yellowing, while in case of elements with darker colours the loss in surface gloss is more visible. More severe phenomena are pitting and blistering of the surface, the formation of micro-cracks, and flaking of the finishing layer. This continues until the finishing layer is removed in its entirety. The effects of UV radiation are furthermore amplified by the degradation of the material caused by temperature, moisture, dust and pollutants. Generally stabilisers are added to the mixture of the gelcoat or lacquer coating, which greatly reduce the sensitivity to the influences of UV radiation. The amount of stabilisers is typically between 0.05 % and 2 % by weight[16] [32].

Temperature and moisture work continuously together degrading the finishing layer and consequently the underlying composite laminate. Assessing both influences separately, these harm the materials in the following manner. Temperature differences between the inside and outside environment on a daily basis, but also over the seasons, cause the element to deflect in- or outwards and consequently cause thermal fatigue in the structural laminate. Furthermore, high temperatures, especially nearing the glass transition temperature (T_g) of both the finishing layer and the composite laminate, increase the visco-elastic behaviour of the layers, causing these layers to be more susceptible for creep and fatigue induced degradation, reduce its mechanical properties, and make it more susceptible to sustaining damage. Very low temperatures cause the finishing layer and the matrix in the composite layer to shrink and to harden, which cause the polymer compound to become very brittle. This makes both layers increasingly susceptible for micro-crack formation. The effects of moisture are initially only applicable on the finishing layer, and in the course of time increasingly noticeable in the composite laminate due to ingression of moisture by diffusion. In the finishing layer and composite substrate absorbed moisture causes chemical changes in the polymer structure. The amount of moisture absorption is mostly dependent on the materials used, the type of liquid, the fibre – matrix interphase, the ambient temperature, the applied stress level, and the extent of pre-existing damage. In the beginning the absorbed moisture increases the effects of creep, lowers the T_g, and starts forming micro-cracks. Consequently it influences the fibre – matrix interphase, causing debonding and thus a loss of integrity in the FRP composite material. As the moisture slowly removes the sizing from the fibres, the fibrous material becomes vulnerable. In case glass and especially aramid fibre is used as reinforcement material, the moisture can degrade the reinforcing fibres, continuously decreasing the mechanical performance of the FRP composite. Over time the absorbed moisture is drawn in to the core material of the sandwich element. Here the gathered moisture has two major effects. On the one hand, the collected moisture may significantly increase the weight of the element, especially in the case the core material has an open-cell structure. On the other hand influences and degrades the by the matrix bonded interface between the FRP composite laminate and the core layer. As this bond decreases in strength, the collaboration between the core and the composite skin also decreases, reducing the strength and stiffness of the entire sandwich element [14] [16] [43].

Together moisture and temperature have more detrimental effects. At increased temperatures the polymeric compounds become softer and show less resistance against moisture. At temperatures below 0 °C a degradation method called freeze-thaw cycling can have devastating effects on the composite laminate, causing extensive stresses in the laminate until it cracks. The effects of freeze-thaw are more severe in salty environments due to the formation and expansion of salt deposits. The effects of temperature and moisture together are grouped under thermohygral degradation. This is often called thermohygral ageing since it is not possible to completely protect the element completely against the effects, the process can only be slowed down. It must be noted that the effects caused by thermohygral ageing are intensified by physical ageing degradation caused by creep and fatigue, and vice versa. A total overview is shown in Figure 4.8 [16] [29] [41] [43].

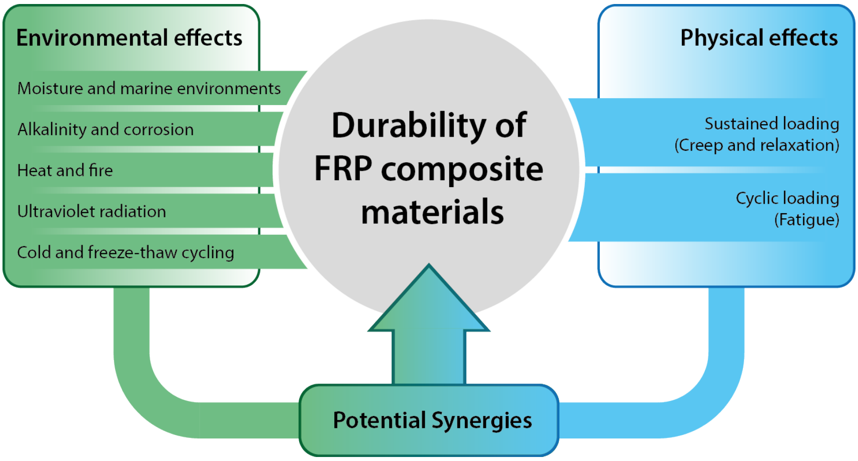
Environmental effects
Moisture and marine environments
Alkalinity and corrosion
Heat and fire
Ultraviolet radiation
Cold and freeze-thaw cycling
Durability of FRP composite materials
Physical effects
Sustained loading (Creep and relaxation)
Cyclic loading (Fatigue)
Potential Synergies

Figure 4.8: Overview of environmental and physical effects on FRP composites [43]

The FRP composite sandwich element can also be effected by chemical degradation, caused by the presence of acidic or alkali substances. The impact of chemical degradation is highly dependent on the material that is used for the finishing layer, but also for the FRP composite laminate, since not all polymeric compounds are susceptible for degradation by acidic and/or alkali compounds. However, since it is highly unlikely that façade elements come in contact with such substances due to natural events or under normal use, this will not be further discussed. Though it must be noted that during construction care must be taken to shield off the installed façade elements in case concrete is poured close by, preventing any contact with alkali liquids and concrete residue[29].

In order to limit the impact of environmental influences attention must be paid to the choice in materials used for FRP composite sandwich element, especially for the finishing layer, but also the design and manufacturing processes contribute to the durability. High quality gelcoats, such as isophthalic based polyester gelcoats, tend to protect the underlying composite laminate to a greater extent than for example an orthophthalic or NPG based polyester gelcoat. Furthermore, the aesthetics of high quality gelcoats can be guaranteed for a longer period. The choice in type of matrix for the composite laminate also has a significant impact on the durability of the element. Several epoxy and vinyl ester based resins are known to slow down the diffusion process of absorbed moisture, although epoxy based resins tend to absorb a relative large amount of moisture, up to 6 % of its weight. With the design of the element the effects of thermohygral and physical ageing should be taken into account in order to minimise the formation of micro-cracks. Additionally, the elements need to be produced with care in order to minimise the void content in the composite laminate, since high void contents in the laminate encourages moisture absorption and diffusion. Besides the initial production the composite material also needs to be cured sufficiently in order to attain adequate resistance against thermohygral degradation[19] [25] [29] [30] [31].

Overall, and this is mainly due to the numerous possibilities in material compositions and production methods, and furthermore caused by a lack of data concerning general characteristics of composite materials regarding its durability and time-dependent behaviour, it is extremely difficult to accurately predict the governing degradation method of the composite material and quantify the impact of all time-dependent influences. Most data regarding the durability of composites comes from tests with high performance composites applicable for the aerospace industry. Since different material compositions and production methods are used for civil engineering applications, the durability of the two ranges of materials cannot be assumed to be the same. However, engineering composite materials have already proven to be fairly durable in civil engineering applications, since they are principally less susceptible to degradation, at least considering environmental influences, when compared to similar applications in metal or concrete[43].

Chapter 5

Production Processes for FRP Composite Sandwich Elements

For the manufacturing of monolithic FRP composite sandwich elements a production method qualifies if it allows for producing sandwich elements, but it should also allow for the manufacturing of monolithic elements with optionally complex shapes. In this chapter an analysis is presented on the available and qualifying production methods, and the possibilities and restrictions that are accompanied with these methods. Thereafter, the interactions between the production methods with the other interdependent factors are assessed.

5.1 Overview of production processes

There is a variety of production methods currently available with which FRP composites can be made. The only thing that all these methods have in common is that some kind of mould is required to give the material its shape as it cures. There are several ways to distinguish the production methods into groups, of which the most used division is made between open mould, closed mould and continuous production methods. With the open and closed mould methods are elements produced that have finite dimensions. The difference here is that in case of open mould production methods the impregnation of the fibre reinforcement happens in open air, while in case of closed mould production methods the impregnation happens in a closed off environment. The enclosed environment is provided by two rigid moulds or by a rigid mould with a flexible cover. With continuous production methods elements can be produced of principally infinite length, and in most cases with a constant cross-section. A second subdivision that is often made is between hot mould and cold mould production processes. It must be noted that often production processes require per definition hot or cold moulds, only in specific cases it is both possible. However, this is completely dependent on the matrix that is used. The choice between the two is then dependent on the desired material properties.

5.1.1 Open mould production processes

The group of open mould production processes contains a variety of production process, namely:

- Lay-up production processes (manual, automated, prepreg, RFI)
- Spray-up production processes (manual, automated)
- Filament winding

First the group of lay-up processes is discussed. Producing FRP composites with manual lay-up, mats with random oriented fibres or woven fabrics are draped onto the mould after which the fibre reinforcement is impregnated with the matrix. This process is executed layer for layer. The maximum fibre volume fraction possible with this method is between 35% and 55% for lay-up processes, though this is also dependent on the fibre reinforcement form, the processing properties of the matrix and the application of a pressure or vacuum bag after impregnation. Pressure or vacuum bags are used to obtain a higher quality, mainly by compacting the composite laminate and reducing the void content. The tooling for manual lay-up production is simple and the costs are very low. This process is also open to automation. In that case a robot places unidirectional with matrix impregnated fibres onto the mould. In comparison with manual lay-up this results in very high quality products with high fibre volume fractions. The downside of this process is that every different shape in combination with the laminate composition needs to be programmed into the machine. The third lay-up method is prepreg lay-up, which is often called autoclave moulding. Pre-impregnated fibre reinforcement, often woven fabrics, are placed manually or by machine onto a mould and a vacuum is applied in order to compact the composite laminate. Consequently the element including the mould are placed into an autoclave to start the curing process, hence the name autoclave moulding. The materials used for this process are named prepregs, and are generally the most expensive materials available for the production of FRP composites. The combination of these materials and processing equipment generates high performance products with high fibre volume fractions of between 60% to 70%, and of the highest quality. However, the necessity of the required tooling and material also makes this very expensive, and in case the prepregs are placed manually also very labour intensive. Furthermore, the labour required for prepreg lay-up needs to be skilled since the process is sensitive to air entrapment, and errors in the placement of prepregs can cause the laminate to distort. A variant of prepreg lay-up is resin film infusion (RFI). With this method a film of matrix material is placed underneath the dry fibre reinforcement. Heat and pressure of an autoclave liquefies the resin, which in liquid form impregnates the fibrous material. This method is easier to execute compared to prepreg lay-up, and also the materials are cheaper than prepreg materials[16] [30] [31] [45] [46].

The second group concerns the spray-up production processes. Spray-up processes, which can be executed both manually and automatically, are a group of production processes where a mix of matrix and chopped fibres are sprayed onto a mould. The length of the fibres (l_{fr}) is generally between 25 and 75 mm. Comparing to the lay-up processes the speed of production is much higher since in most cases the entire composite laminate is sprayed onto the mould at once. Thicker laminates may require two or more layers. However, for spray-up processes the maximum fibre volume fraction is generally lower than 35%. The low fibre volume fraction and the application of random oriented short fibres make this production process only suitable for low- to medium-strength structural elements. Also if this process is executed manually the end-result is to a great extend dependent on the skill of the person handling the spray-gun. It is rather difficult to obtain a smooth surface and low tolerances in thickness with manual application. Automation of this process guarantees a somewhat higher and more consistent quality. Due to the rough surface of the resulting composite laminate, an element that is manufactured with a spray-up process needs to be further processed before it can be supplied with the final finishing layer[16] [30] [31].

The third group exists solely of filament winding. Filament winding is an automated process where with matrix impregnated continuous fibres are spun around a rotating mandrel. This process is principally only used for the production of hollow cylindrical elements, such as pipes and tanks, and does not allow for complex shaped sandwich elements, and will therefore not be further discussed.

All lay-up and spray-up processes are considered to be very flexible production methods, and with these methods the production of sandwich elements with complex shapes is possible. Generally, the tooling costs, especially when executed manually, are also very low, with exception of an autoclave in case of the application of prepreg lay-up. The curing process for both production methods can take place at ambient and at elevated temperatures. In case of the latter, principally a cold mould system is used and the product is then cured in an oven or autoclave. Lay-up processes are often more labour intensive and time consuming than spray-up processes, but result in a product with higher strength and generally of higher quality. Both lay-up and spray-up processes are mostly used for prototyping and small- to medium-volume production[16] [31].

Some general but important issues need to be addressed regarding open mould production processes, namely the safety during processing and the finishing of the FRP composite products. Firstly, it must be noted that during the processing of the composite material the open mould processes allow for the release of volatile gases. Especially styrene emission is a major concern. Also if the matrix is applied manually, the process is considered to be not a clean process and additional protection is required for the people handling the materials. This is similarly applicable for handling prepreg material and the spray-up processes. The second issue is the finishing of the composite elements produced with open mould production processes. A gelcoat can only be used in combination with rigid moulds, and due to the fact that only one rigid mould is used, the surface area of the element that is not in direct contact with the rigid mould cannot have a gelcoat. This surface area tends to be rough and requires further processing before the element is completely finished[16] [31].

5.1.2 Closed mould production processes

In the group of closed mould production processes belong:

- Compound moulding processes (injection, compression)
- Liquid infusion moulding processes (RTM, LRTM, VARTM, TERTM)

Injection moulding and compression moulding are two types of production processes that both make use of solid moulding compounds. Moulding compounds are a premixed combination of matrix and a filler material that serves as reinforcement. The reinforcement forms for these production methods are restricted to short to very short fibres, particles and flakes, continuous fibre reinforcement cannot be used. However, moulding compounds are required to be injected under pressure into a mould, or compressed between two rigid moulds in order to obtain its final shape. Although complex shapes can be obtained this way, these production methods do not allow for the production of sandwich elements and will therefore not be discussed in further detail[16] [30].

Liquid infusion moulding production methods are mostly referred to as resin transfer moulding, or RTM. With this production method, the fibre reinforcement is placed into the mould and then closed off completely from the outside environment. Consequently, liquid matrix is injected into the mould until the entire reinforcement is impregnated with the matrix. Since the impregnation of the fibres happens in a closed environment the release of volatile emissions is very low. There are several variants of this process. The default version is basic RTM where the reinforcement is placed in between two rigid moulds and the matrix is injected under pressure. Light RTM (LRTM) and vacuum assisted RTM (VARTM) make use of a vacuum in the mould to draw in the matrix in the mould and impregnate the fibre reinforcement. The difference between these two methods is that VARTM makes use of two rigid moulds, which together with the vacuum allows the matrix to be injecting under pressure into the mould, and LRTM makes use of a rigid bottom mould and a flexible top mould. Thermal expansion RTM (TERTM) is again a variant on RTM or VARTM. This process is exclusively used to make sandwich elements, and uses heated moulds in order to make the core material to expand after the injection process of the matrix is completed, compressing the composite skin in order to obtain a higher fibre volume fraction and thus a stronger laminate. All RTM production processes allow the production of sandwich elements with complex shapes, and with exception of LRTM, the entire exterior surface of the element can be covered with a gelcoat. Principally all types of fibre reinforcement forms can be used with RTM production processes. For low performance elements generally only random fibre mats are used. Elements produced with this form of fibre reinforcement are part of the group of standard RTM elements. Elements with higher performance requirements demand a more complex laminate design with UD fibre and/or fabric reinforcement. At optimal circumstances fibre volume fractions up to 70% can be achieved. Such elements are part of the group of advanced RTM elements. RTM production processes do put restrictions on the use of matrices. These range of processes can only be used with low viscosity matrices, between $\mu_{mx} = 0.1$ Pa · s and $\mu_{mx} = 1.0$ Pa · s, and dependent of the size and the complexity of the shape of the element, and on the viscosity of the matrix, very long gel-times are required, which can add up to over an hour. Generally matrices with a viscosity of μ_{mx} 0.5 Pa · s or lower are used[6] [16] [30] [31].

Compared to other closed mould production processes, RTM production processes have relative low investment and tooling costs, especially when the production and curing of the elements occur at ambient temperatures. This group of production processes is also suitable for prototyping and for production of elements at intermediate volume rates. Though these costs are generally higher than the mould and tooling costs of lay-up and spray-up production processes. With some additional effort elements with varying shapes can be made with one mould by placing infill-blocks in the mould. Varying shapes and increasing complexity of the shape of the elements do have a negative effect on the cost and production rate. Manufacturing complex shaped elements with an RTM production process also requires or trial-and-error experimentation of flow simulation modelling. This is necessary to prevent unimpregnated parts of fibre reinforcement and a high level of porosity in the composite laminate. Dry areas and curing of the matrix before the cavity is completely filled are two of the main problems that can occur during production. Furthermore, asymmetrical design of the fibre reinforcement over the thickness of the laminate and fibre wash away due to the flow of matrix during impregnation can both cause residual stresses in the laminate during cure, which consequently can cause the laminate to warp. The level of deformation is dependent on the height of the residual stresses[31].

5.1.3 Continuous production processes

In the group of continuous production processes belong:

- Pultrusion
- Pullshaping (braiding, pullforming, pullwinding)

- Continuous laminating
- Sandwich foam co-extrusion

On the one hand continuous production processes are very flexible, but on the other hand they are also very limiting. With pultrusion, pullshaping, pullwinding and braiding line-elements are made. The cross-section of these elements can have endless shapes and it is also possible to produce hollow sections. The limiting factor, however, is that pultrusion does not allow any variations in cross-section over the length of the element, and pullshaping only allows small variations. With these production methods it is furthermore not possible to make sandwich elements. Braiding and pullwinding, while similar to pullshaping, do allow for larger variations in the cross-section, but do also not allow for the production of sandwich elements. Continuous laminating and sandwich foam co-extrusion are used to make plate-elements. Both production methods are not suitable to make elements with changing cross-sections over the length of the element. Also, though it is possible to manufacture FRP composite sandwich elements with sandwich foam co-extrusion, this process it is not suited to make complex shapes. Since none of the continuous processes can be used to make monolithic FRP composite sandwich façade elements, these processes are not further discussed[30].

5.1.4 Overview qualifying production processes

In the end, the production processes that are suited for the production of monolithic FRP composite sandwich elements are the lay-up, spray-up and liquid moulding processes. An indication of the differences in performance of the elements produced with the production methods, and in cost-efficient production volumes of the production methods is presented in Figure 5.1. Here a distinction is made between on the one side manual and automated lay-up processes, and on the other prepreg lay-up, mainly due to the large difference in performance of the resulting element. The same is applicable for standard RTM processes and advanced RTM processes, as is mentioned earlier.

Low production volumes are considered to be applicable for prototyping or the production of up to a couple of hundred elements. For such production volumes generally lay-up processes are used, and in some cases a liquid moulding process. Of the methods mentioned above the liquid moulding processes are an appropriate choice for intermediate production volumes of values of a couple of hundred to a couple of thousand elements.

Each of these production processes may be used to manufacture large and complex shaped sandwich elements. However, only with the closed mould processes, such as RTM, VARTM and TERTM, elements can be produced that have a gelcoat finishing layer on all sides.

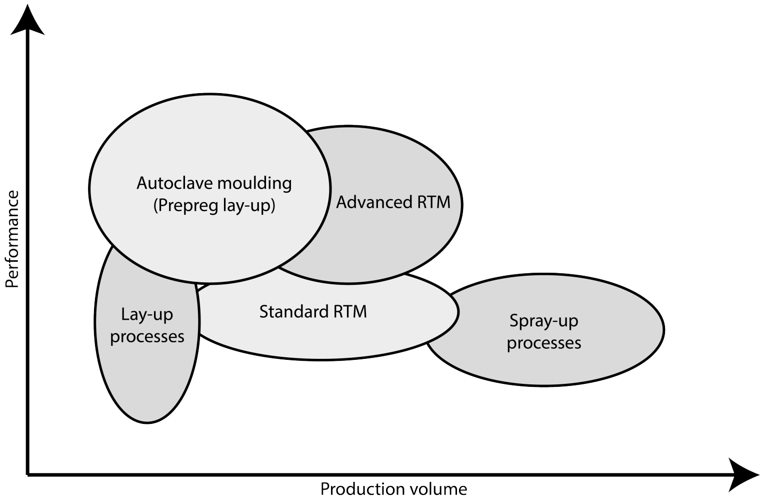

Figure 5.1: Comparison of the qualifying production processes [30]

5.2 Assembly of the components

Interaction of the separate components, the window or windows, the anchor construction and the weather-tight sealing, with the sandwich element is fairly limited during the production process of the sandwich element. Principally all components are mounted on the sandwich element after it is finished. Looking at the assembly process, it is advised that the final shape of the sandwich element is changed as little as possible when the remaining components are mounted. This is the case for clamped and glued connections, which have been discussed in Section 4.3. Important here is that the surface of the sandwich element is cleaned properly before assembly. However, in case bolted and/or screwed connections are part of the design, the holes for the fasteners need to be pre-drilled, which can be considered part of the production process of the sandwich element. Besides discontinuing the reinforcement in the composite laminate, drilling, cutting or sawing in the composite material can be a starting point for an increased rate of deterioration in service. Machining holes in the composite laminate may initiate delamination or cause the laminate to splinter. Furthermore, the heat that is released during processing may cause initially discolouration, and exposure to heat from the drilling and sawing can make the composite material more susceptible to creep and fatigue [30].

The placement of brackets or plates can make a large difference in this case. Completely integrated brackets have a relative small effect on the performance of the composite laminate and the sandwich element as a whole, since only a couple of small holes need to be drilled for the fasteners. Partially protruding brackets require much larger holes, and especially when the brackets are mounted into the sandwich element after the composite laminate is cured. Such brackets may cause major weak spots in the composite skin of the sandwich element, both mechanically as concerning the durability of the element.

5.3 Technical specifications and requirements for production

First of all the sandwich element has to fulfil a set of demands concerning the strength and stiffness of the element. Although according to theory a designed element has a strength and stiffness equal or larger than the requirements, the final performance of the element is very much dependent on the course of the production process. This is applicable for short term behaviour, such as mechanical and thermal performance, but also on long term aesthetics and durability. In order to make sure the quality and the performance of the elements are according to a certain level, a continuous quality control needs to be performed on the materials used, the production process itself, and the resulting products. The quality assurance concerning the production process of FRP composite sandwich façade elements is discussed in the third part of this thesis. It must also be noted that the design of the element has a much more tangible interdependent relation with the technical specifications and requirements than the production process. Although, the production method determines the resulting quality of the elements, with the design the intended physical properties of the elements are determined.

5.4 Possibilities and restrictions on shape and design

Application of monolithic FRP composite sandwich elements creates a new line in unitised façades systems, which has the potential to be a competitive alternative to other unitised façade systems, perhaps even to other non-unitised systems. Generally spoken this type of element can be produced in any form, following the flat and curved surfaces of the façade of the building. In principal it is even possible to produce double-curved or in-plane twisted façade elements, which is generally not feasible with aluminium or steel framed façade systems. However, some issues considering the relation between the architectural design and the production process are of importance, and are discussed in the following sections.

5.4.1 Effects of the design on the production process

First of all, buildings often require having a unique appearance with two or more different surfaces or non-consistent surface lay-outs. This leads to different façade elements. With constant outer dimensions, and dependent on the production process, elements with different lay-outs can often still be made with a single mould. The differences are then handled with so-called infill-blocks. As the outer dimensions or the curvature of the plane changes, then for every element a separate mould is required. The main issue here is that this makes the overall design and production a very costly process. Similar to the production of other unitised façade systems, the overall costs can be kept low by using large amounts of the same element in a design. The second issue applies to the details of the design of the sandwich elements, specifically the sides around the optional infill-blocks and at the outer perimeter of the element. For both open and closed mould processes it is pertinent that the slope and shape of the sides are a determining factor on the ease of release of the composite element after it is set. Potential problems are shown in Figure 5.2 and Figure 5.3.

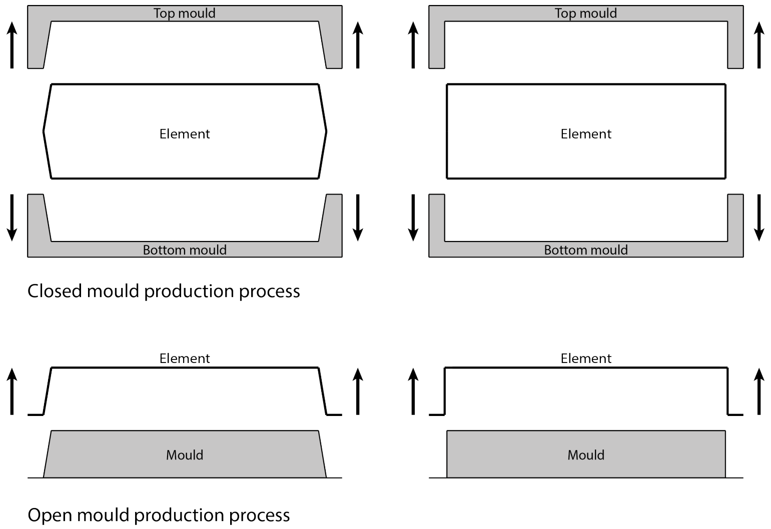

Figure 5.2: Simplified visualisation of the release process of elements with sloped sides (left) and right-angled sides (right)

The sides of the element, or principally all out-of-plane surface areas that are covered in FRP composite material, tend to be sloped. The slope, also called the draft angle, ensures an easier proceeding release process, and is advised to be at least 1°. Larger draft angles improve the material flow in closed mould production processes and reduce potential warping of the sides. In case the out-of-plane surfaces do not have a slope the friction between the element and the mould may cause damages to the surface of the element. This is mostly relevant to the sides around infill-blocks due to shrinkage of the composite material during curing. It must be noted that overall the mould needs to be larger than the final element in order to take shrinkage of the composite laminate into account. Although it is dependent on the materials used and the composition of the fibre reinforcement, the total shrinkage is often not more than a few per cent. Therefore, the in-plane dimensions of the element are required to be adjusted for this material specific behaviour, the total reduction of the thickness of the element is much less prominent [31].

The cross-section of the façade elements may contain convex or concave shapes in the out-of-plane surfaces, which may be there for clamped or glued connections with one of the critical components. During the design of these connections it is important that the required shapes for the connections, or even for aesthetical reasons, still allow the element to be released from the mould [31].

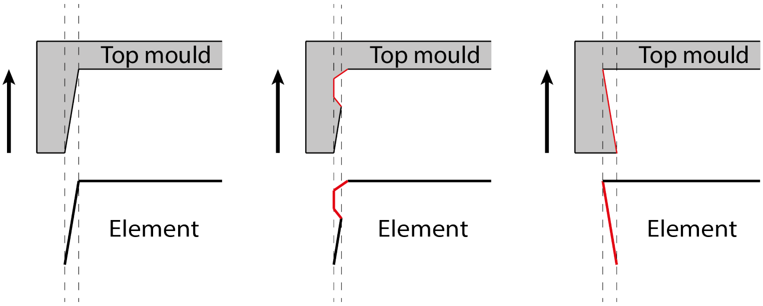

Figure 5.3: Indicative representation of conflicts during release due to convex or concave shapes at the sides of the element

For elements that contain shapes conflicting with the release process, there are solutions that make the manufacturing of the elements still possible. Around the edge of the element infill-blocks can be placed and the infill-blocks in the middle of the element can be made modular. This solution does complicate the production process, creates edges in the finishing layer, increases the chance of inconsistencies and failure, and increases the cost and required labour. These consequences make it advisable to limit or completely exclude the use of modular infill-blocks in the production process.

5.4.2 Design constraints generated by the production process

When façade elements are considered plate-elements, using monolithic FRP composite sandwich elements the design possibilities are principally infinite. However, focussing on the cross-section of the elements there are some limitations that have to be considered. Firstly, for façade elements that contain large areas of glass, the composite sandwich part takes more the form of slender beams that hold the windows in place. Slender composite structures can pose problems for the production of the element. Very small areas of composite material around the windows lead to very tight spaces in the mould, which can make it hard or impossible to work in. For the application of the release agent, and when applicable the gelcoat, require tooling, which consequently require a certain amount of space in order to be applied properly and to allow for a proper visual check on the quality of the applied layers.

Secondly, the radii of the corners and edges of the composite laminate play a significant role during the production process and the performance of the element. Sharp corners are advised to be avoided since these are very sensitive to damage during the production and during the service. The inner radii (r_i) should be at least 2.0 mm, for the outer radii (r_o) the minimum value is 1.5 mm. However, as the radii of the edges and corners become larger, the interlaminar tensile and shear stresses in the laminate decrease and the interlaminar strength increases. The application of larger radii decreases the chance of micro-cracking and therefore increases the durability of the element. Furthermore, large radii have a positive influence on the flow of matrix in closed mould production processes, and ensures the element to be released more easily from the mould[21] [26] [31].

5.5 Interaction between production and environment

The environment is influenced by the production process and vice versa. The production process itself is always influences by the local climate, which is basically always indoors. Logically, the temperature and relative humidity of the local climate has more influence on open mould production than on closed mould process. However, differences in temperatures and humidity during the preparation and production of multiple elements cause differences in strength, stiffness, durability and outer dimensions between the elements. The magnitude of the differences is dependent on the degree of change in climate, the curing and post-curing process, and also in the materials used and the composition of the composite laminate during the total production process. A guaranteed continuous quality is therefore dependent on the stability of the interior climate.

The production of FRP composite containing elements also has an influence on the environment, though here it involves the local or interior climate, and the global environment. Locally it is important that working with this material often includes working with toxic and/or volatile substances. Furthermore, during curing of the composite material release of toxic gases is a common occurrence. Working with composite materials requires safety equipment, such as gloves and in some cases breathing equipment with special filters, and a sufficiently ventilated production facility. Concerning the use of thermosetting resins applicable for the building industry, the most common volatile gas that is emitted by the resin as it is curing is styrene. In small amounts and brief exposure this gaseous material is not really harmful, but as this gas reach higher concentrations and in case of longer and more frequent exposure it creates an unhealthy and unsafe work environment. This substance is known to cause respiratory problems and illnesses, cause interference in the central nervous system, and some studies infer that this specific volatile has shown signs of carcinogenicity. Styrene is not necessarily the only harmful substance used in the entire production process. It is therefore prudent that all materials that are part of the production process are reviewed and the necessary precautions are taken[52] [53].

Another aspect of influence that the production process has on the environment is the use of energy during the entire production process. In some cases the production process can be adjusted to meet the pre-set requirements. Of the entire process the curing procedure has, due to its flexible setup and the available possibilities, the most influence on the total energy demand. By applying an extended curing program at elevated temperatures, and possibly under heightened pressure, the quality and mechanical properties of the composite laminate can improve significantly, but as a consequence the overall energy requirement will increase as well. Though, this is not as life-threatening as the matter discussed above, it is something that has to be considered as the elements and accompanying production processes are designed.

Chapter 6

Critical Components of FRP Composite Sandwich Façade Elements

The critical components that are required to manufacture a complete unitised façade element, besides the composite sandwich element, have already been discussed a couple of times in the previous chapters. It concerns the windows, the sealing around the element and the anchor construction, of which an overview is given in Figure 1.2 Chapter 1. Generally it are not the components themselves that cause problems in the production process. The way the components are connected to composite sandwich element and how they allow for assembly can have major consequences. The type of connections and their (dis-)advantages have already been discussed extensively in Section 4.3. This chapter elaborates on the features of the components and the possibilities and considerations in accompanying connection types.

6.1 A brief overview of the components

In this section a brief overview is given of the critical components. It is also indicated in which manners these components can be mounted onto the composite sandwich element and what the potential consequences are.

6.1.1 Weather-tight seal

As with all unitised systems the monolithic FRP composite sandwich façade elements require a weather-tight seal around the element. This seal perfectly interlocks with the elements around it when the element is installed, and ensures the façade to be air- and watertight. The weather-tight seal generally consists out of multiple rubber profiles, sometimes in combination with steel or aluminium profiles for additional rigidity, creating three or more barriers.

Currently most unitised façade systems consist of a bearing aluminium frame on which glazing and infill panels are mounted. The sealing around these façade elements are generally clamped or clicked in a crevice in the aluminium frame that surrounds the entire element. An example of this is given in Figure 6.1. Applying the same system on the monolithic FRP composite sandwich façade system, and creating three barriers at the same time, one or multiple crevices need to be made in the elements. As this causes shapes in the side of the element that conflict with the release process, this can be solved by applying infill-blocks surrounding the element in the mould. This method creates a proper solution for the application of the weather-tight seal without creating weak spots in the finishing layer and composite skin of the element, but does complicate the production process significantly.

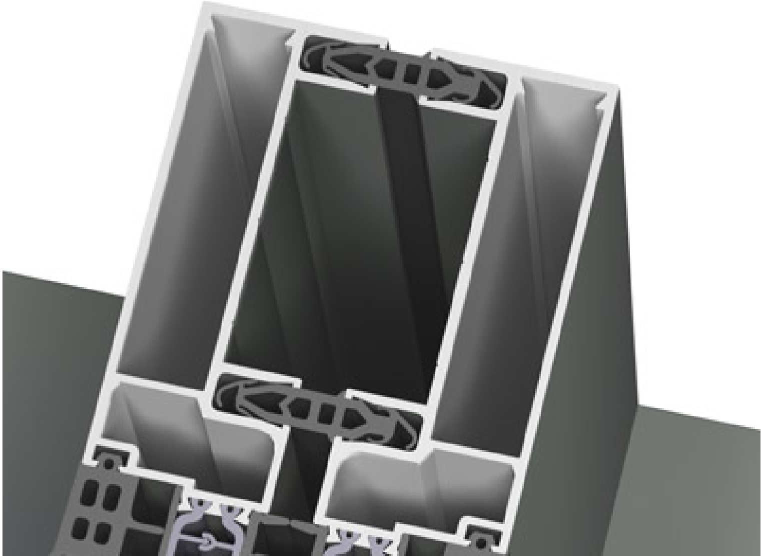

Figure 6.1: Clamped rubber profiles serving as barriers as a part of the weather-tight sealing between aluminium profiles[47]

Secondly it is possible to glue the sealing around the element. Depending on the design of the seal the glued area will or will not be subjected to weather influences. Due to improper preparation of the surface of the element prior to gluing, or in case the glue is applied incorrectly, the weather-tight seal is susceptible for the forming of leaks. Since the sealing does not have a structural function it is not likely that the connection will fail due to excessive tensile, shear or peel stresses.

The last option is to mount the seal onto the element with screws, which potentially can be combined with a glued connection. For this type of connection it is advised to combine the rubber profile with a metal profile in order to guarantee an airtight connection over the entire length of the seal. In case a metal profile is part of the weather-tight seal, the differences in thermal expansion between the seal and the composite sandwich element must be taken into account, this may cause some additional stresses at the locations of the screwed connections. A major downside of this type of connection is that the finishing layer and the composite laminate are perforated by the screws. Consequently, and also dependent on the design of the seal, the element might be susceptible to an increased rate of deterioration due to penetration of moisture in the element itself.

6.1.2 Glazing

In unitised façade systems there are principally two types of glazing, namely framed glazing and structurally glued glazing. Framed glazing can make use of metal, generally aluminium, wooden or plastic profiles to hold the glass pane in place. As for structurally glued glazing the glass pane is glued directly on top of a frame, in this case the sandwich element. Here only the connection between the frame and the sandwich element for framed glazing, and the glass pane and the sandwich element for the structurally glued glazing are discussed.

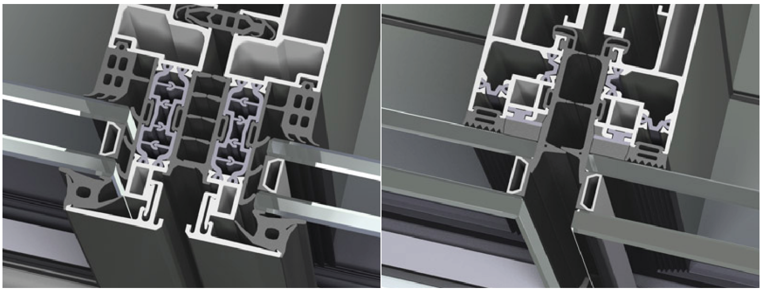

Figure 6.2: Example of connections between aluminium profiles and glass panes; Clamped connection (left), structurally glued connection (right) [47]

In case an additional frame is applied around the glass pane, the simplest method of linking the frame to the sandwich element is to clamp it onto a protrusion in the sandwich element. Combining this connection with glue or screws may result in a fixed and more reliable coupling, but also adds to the effort required for the assembly of the façade element. Furthermore, the application of a screwed connection also damages the composite laminate of the sandwich element.

Structural glazing is principally always glued to the bearing structure, in this case not an aluminium frame but a monolithic sandwich element. Gluing the glass pane to the sandwich element may contribute significantly to the overall stiffness of the element, especially in case the transparent surface area takes up most space and the sandwich element is nothing more than a framework consisting of slender mullions and transoms. Important here is that the connection between the glass and the sandwich element needs sufficient mechanical strength, but it also serves as a weather-tight seal. The surface treatment of the sandwich element necessary for creating an adequate bond can range from light sanding and cleaning of the finishing layer up to complete removal of the finishing layer if this is required to provide a sufficiently strong connection. This is of course dependent on the preferred glue and the interactive properties of the glue with the applied finishing layer, but also on the adhesive integrity between the finishing layer and the structural laminate underneath[7] [31].

Additionally to what already has been considered and is relevant for the design of the connection with the windows is that these transparent surfaces often cover large areas of the façade. As these large glass surface are also subjected the wind load, the resulting forces need to be transferred from the windows to the sandwich element. The introduction of the forces into the composite laminate of the sandwich element is very much dependent on the design of the shape of the sandwich element, and on the applied type of connection or combination of types of connections. What needs to be considered here is that FRP composite laminates have a relatively low capacity of dealing with stresses with an out-of-plane directionality. This is, however, one of the design challenges accompanying the application of this material. Obviously the dead weight of the window construction must also be considered during the design of the connection.

6.1.3 Anchor construction

The anchor construction comprises all components with which the façade element is mounted to the bearing structure. In order to simplify the installation of the façade elements, the mounting system is kept is basic as possible, commonly per connection composed of a bracket, which is fixed to the bearing structure, and a component mounted to the façade element that hooks in the bracket. The anchor construction is crucial to function at all times, as failure means that the element could fall off the building. For the mounting system itself numerous methods are available, for the connection between the FRP composite sandwich element and the component that is supposed to hook in the bracket this is not the case. This component can be composed of only an external part, or an internal and external part, where the internal part is incorporated in the sandwich element during production. Considering mounting this component to the sandwich element with fasteners, the component made up of an internal and external part is bolted together, in case the component exists of only an external part it is screwed to the sandwich element. Both these connections can be combined with a glued connection, and in case no internal part is present a glued connection between the component and the sandwich element could be sufficient.

There are two logical alternatives for the traditional methods discussed above. Firstly it could be possible to incorporate a metal component in the sandwich element, which is completely embedded in the sandwich element or protrudes the element slightly, and serves as the component that hooks in the bracket on the bearing structure. A second alternative is to design the sandwich element in a way that the bracket can be linked to the sandwich element without screwing, bolting or gluing a component onto the sandwich element.

Anchor constructions are a complex subject, even more so in combination with a relative novel building material. Although, it is easiest to rely on proven methods, FRP composite materials do generally not behave as the materials the proven methods were designed for. Optimising the anchor construction for FRP composite sandwich elements requires acknowledging the advantages and disadvantages of the used materials. First of all the way the forces are transferred from the façade element to the bearing structure, and thus the location the connections latch on to the façade element, can have a significant influence on the capacity of the anchor construction. This behaviour is also considered in the material assessment. Another issue might be the available space and possibilities for the connection to the bearing structure due to the design of the element. Unless boundary conditions are set for the design of the façade element regarding the necessary available space for the anchor construction, certain flexibility in the design of the components for the anchor construction may be required. Nevertheless, the anchor construction for such façade elements actually requires much more research in order to optimise this critical component. The scope of this is considered of a too large extent and will not be further discussed.

6.2 Technical specifications for the critical components and connections

Concerning the technical specification and regulations for the components and each connection with the sandwich element, the requirements show great similarity with the requirements for the materials used in the sandwich element and the element itself. These range from demands concerning the strength and stiffness for the anchor construction and the windows, up to several minimum specifications concerning the building physics properties of the windows and the sealing around the sandwich element. These regulations are previously discussed in Section 4.4.

6.3 Interaction between the critical components, the connections and the design

The critical components and the manner these are intended to be connected to the sandwich element experience a great deal of interaction with the details of the design of the monolithic sandwich element. The systems for the sealing and the anchor construction are to some extent suitable for standardisation, the design of the window construction can be assumed to be different for each project. The most recognisable influence the components and the connections have on the sandwich element, and then especially on the structural laminate, is the amount and directionality of the loading the sandwich element is subjected to. However, the development of a standardisation of the anchor construction and sealing is not part of the scope of this analysis. Furthermore, as for the windows, due to the numerous amount of variables and possibilities in the design of the façade elements, it is nearly impossible to come to a useful standardisation for this component, though it can be assumed that the degree of complexity of the designs has a direct influence on the complexity of the critical components and the accompanying connections. A practical recommendation that can be made concerning this subject are simplicity in the design of the connections and the corresponding cross-sections of the sandwich element, as this reduces the complexity of the production and assembly process, and at the same time reduces the chance of failure.

6.4 Critical components and the environmental influences

Again, concerning the interaction between the components and the environment, the connections are the part of the structure that is of interest for this specific subject. In this section two issues are examined, namely the influence of the environment on the components and connections, and the required behaviour of the components and connections regarding the exterior climatic conditions. Firstly, dependent on the design the connections between the sandwich element and the components can be exposed to the external climate, which consequentially had the potential to increase the speed of degradation of the connection itself and/or the connecting components. Especially moisture in combination with FRP composites has the tendency to penetrate unsealed holes and porous surface areas. This requires connections with fasteners to be sealed properly in order to prevent any ingress of water. The same consequences are of a higher magnitude as the moisture contains corrosive agents, such as acidic and alkaline fluids. The presence of these corrosive agents in high concentration is for the application in façades a rather unlikely scenario. Another applicable environmental factor concerns the temperature conditions. The connections need to be able to handle any differences in values of the coefficient of thermal expansion (CTE) of the critical component and the sandwich element. Large differences in CTE can lead to large differences in deformation and subsequently significant stresses in the connection and connecting components. Bolted and specifically screwed connections may introduce high stress concentrations in the composite laminate and in extreme cases cause damage to the sandwich element[7].

The second issue concerns one of the main functions of the façade element in its entirety, namely to create a weather-tight seal and sufficient thermal resistance between the interior and exterior climate of the building. The weather-tight seal is realised by means of the seal located around the sandwich element, but also by the connection between the seal and the sandwich element, and the connection between the window construction and the element. This requires some consideration during the design process, but also careful execution of the assembly process and verification of the seals by means of regular quality control. Reaching a sufficient thermal resistance over the entire element is a different story. The window construction and the sandwich element alone are not the problem, these parts are designed with a sufficient thermal resistance without any difficulty. The transition areas between the window construction and the sandwich elements and between the façade elements have a high risk of forming thermal bridges. This potential problem is, however, similar to what can occur at the corresponding transition areas in aluminium framed unitised façade systems, and can be prevented in the design stage with thoroughly executed simulations and existing solutions[7].

Chapter 7

Technical Specifications and Requirements

As with all aspects of the building industry, the design and production of façade elements is surrounded with national regulations and minimum requirements. The demands are often complemented with specifications and increased requirements set by the client. In this chapter the general requirements and regulations are reviewed, and potential interaction with the other aspects is briefly discussed.

7.1 Specifications and requirements for façades in general

The general specifications and requirements for façades are for a large part already discussed in Section 4.4. As is mentioned the minimum values for the requirements are mostly set by national or international standards. The requirements applicable to façade systems are summarised below.

Beginning with the static behaviour of the elements, the elements of a unitised façade system need to have sufficient strength to carry its own weight and to resist the wind load. The characteristic wind load is described in standards and dependent of the region and height of the building. The elements also need adequate stiffness. Generally the deflection (w) caused by horizontal loading must remain below $L/300$, with a maximum value of $w_{max} = 15$ mm. Following VMRG Quality guidelines regarding the maximum deflection of elements with very large spans, the maximum deflection is defined by $w \leq L/250$ [mm], for $L > 7.5$ m[54].

The demands in consideration of durability can be briefly summarised. The façade elements are designed for a certain lifetime, often for 25 or 50 years. During this period the elements are not allowed to fail, with the exception of unforeseen and extreme causes. This mainly concerns withstanding all long-term influences, meaning, failure due to fatigue or creep, though these types of behaviour are material specific. Following the various guidelines for the application of FRP composites in the building industry, these aspects are taken into account in the form of safety factors for the determination of the strength and stiffness of the laminate. Currently for FRP composites in standards provided models concerning creep and fatigue, that are unambiguous and by research sufficiently substantiated, are not yet available.

The minimum requirements concerning the building physics of the façade elements, cover values for the weather-tightness and thermal resistance, and are determined by national standards. These topics and their minimum values have been assessed in Chapter 4. The demands considering fire safety are also already discussed. Assuming unitised façade systems are generally applied on buildings taller than thirteen meters high, a brief recap of the requirements for the façade elements concerning fire safety, which are applicable in Europe, comes to a minimum of fire class B for the entire element, and additionally a minimum of smoke class S2 for the interior surface area of the elements.

7.2 Dependency of the design and shape on the specifications and requirements

One of the major reasons to choose façade elements made from monolithic FRP composite sandwich is for its distinctive aesthetical appearance. The opaque sections of the elements have level planes, smooth curved surfaces and clean lines at the edges. Dependent on the shininess of the surface area, imperfections are relatively easy detected. Amongst these imperfections are inconsistent shapes and dimensions, undesired rippling or bubbles of air in the finishing layer, and differences in colour and gloss. The exact terms of these requirements are principally always set by the client, and apply on the elements on delivery and installation. It is possible that additional demands are made for the aesthetical appearance over a longer period, for example retaining or limiting alteration of the colour and degree of gloss of the finishing layer.

7.3 Technical specifications and requirements related to the environment

Regulations concerning façade elements interacting with the environment comprise for a large part the required durability of the elements. The façade needs to stay in place and execute all its tasks for the period it is designed for, for example 25 years. Every natural influence, sunlight, rain and temperature variations, need to be coped with, without showing any form of physical damage. This requires a lot from both the structural composite laminate and the finishing layer of the sandwich elements. In the case the structural layer experiences micro-fracturing or local fibre debonding, for example due to creep or fatigue, the finishing layer needs to keep forming a closed cover to avoid accelerated deterioration. Creep and fatigue behaviour of the structural laminate can be tested with the test methods described in standards. This is further discussed in second part of this thesis.

Restrictions in degradation of the finishing layer due to weathering, and then especially UV radiation, can be specified with values resulting from physical tests that are in accordance with the corresponding standards. For these tests, machines are required with which the accelerated weathering is simulated. Also there is another environmental influence that has an impact on the behaviour and durability of the sandwich element regarding the colour of the element. The thermosetting resins used as a basis for the structural layer have a maximum continuous-use temperature, which is rather low and determined by the glass transition temperature (T_g) of the matrix. This property must have a higher value than the maximum temperature influence during summer conditions as is described in regional or national regulations. The maximum temperature influence describes heating up of the façade element due to a combination of the exterior temperature and direct sunlight. Direct sunlight has an increasing influence on the heating up process as the colour of the exterior surface area of the façade element becomes darker, meaning, for the production of white elements a matrix with a lower T_g is allowed than for the production of a red or black element. Testing the materials for their behaviour regarding weathering and maximum continuous-use temperatures is normally done in accordance with the associated standards. These material properties and accompanying test standards are also topics in the second part of this thesis.

Legislation concerning the influence the façade may have on the environment are generally limited to a minimum value for the thermal resistance. Here a distinction is made between the window constructions and the closed parts of the façade. The minimum required thermal resistance of the closed part, the sandwich element, is generally set nationally. The actual value of the thermal resistance of the sandwich element is calculated by hand or with help of computer simulation, with as input the thermal conductivity (λ) of each of the layers. Determination of this property is normally done according to test standards, but this subject is not further discussed.

Chapter 8

Shape and Design of FRP Composite Façade Elements

In the final part of the system analysis the design of this type of façade elements is discussed. This chapter contains an analysis of the design characteristics and of the interaction between design choices and the environment.

8.1 Design possibilities and limitations with FRP composite sandwich elements

FRP composite is often posed as a material with limitless options in shape and design. Basing a façade system on FRP composite sandwich elements does allow for a lot of freedom in design. It is not only possible to manufacture the previously mentioned double-curved façades, it is even possible to produce free-form façades. Regardless of the shape of the elements, the end result of correctly produced composite sandwich elements consist of smooth surfaces, seamless transitions and a clean finish. Complexity in design does come at a cost as one would expect. The amount of variation in the design directly influences the required amount of moulds, or in the best case only adaptive moulds. However, and as is discussed in Section 5.1, there are some issues that need to be taken into account during the design process, mostly related to the required space to apply all the layers of the sandwich element and the radii of the edges and corners. Furthermore, the in-plane dimensions of the element have a maximum, which is mostly limited by transport options. Furthermore, the application of larger façade elements lead to increased margins around the elements, and the sandwich elements are then also subjected to larger stresses and deformations, consequential to both temperature differences and dead weight.

8.2 Design and environment

One of the key characteristics of FRP composite sandwich elements is that it is rather easy to obtain high values of thermal resistance, although in order to reach values for thermal resistance R_c = 10 m_2K/W or even higher, this requires the elements to become fairly thick and massive. However, the thickness of the core is not always optimally used in the design from a thermal perspective, especially in case the framework of the element is constructed of very slender mullions and transoms. As heat and cold penetration follows the shortest route through the element, in ill designed elements it can occur that the shortest route is just around the edges of the glued glazing or window frame, creating considerable thermal bridges.

Continuing with thermal influences, the overall design of the façade has a notable influence on the maximum deflection of the elements due to differences in temperature between the interior and exterior climatic conditions. The further apart the inner and outer composite laminates are positioned from each other, the smaller the expected thermally induced deflection is. Here it must be taken into account that the colour of the external surface area also has a moderate to high influence on raising the temperature of the outer laminate, and thus on the maximum deflection during summer conditions.

Chapter 9

Analysis Overview and Concept Optimisation

The analysis of FRP composite sandwich elements in the façade industry has shown that, although it is a complex system with numerous factors with interdependent influences, a few factors stand out from the rest. These factors take in a critical position in the entire process. Besides these key factors there are a couple of associated influences that have the potential to have a large impact on other factors as one or more aspects of the original factor change. Consequently, an optimisation of these key factors can have a major influence on the total cost of the design and production of such sandwich elements, and therefore on the entire manufacturing process of the façade elements. However, the decrease in costs will fluctuate dependent on the design and requirements. Therefore, in this research no quantification is given, quantification is only possible on a project-by-project basis. The key factors and influences, and the optimisation options are discussed in this chapter.

9.1 Key factors and interdependent influences

Although a monolithic FRP composite sandwich element is actually only a part of an complete façade element, the use of a specific combination of materials and a corresponding structure of layers of the sandwich elements is here defined as a concept for the entire system. As the introduction and state-of-the-art have shown, it is quite difficult to compile a working concept with the available knowledge and present day technology. The factors and influences that have a key position in the development of the working concept are the matrix, and especially in contrast to durability, the fire behaviour of the element, the production process, and the connections with the critical components.

During the analysis it is made clear that the matrix is the most obvious and important key factor, since this polymeric compound is responsible for both the structural layer and integrity with the finishing layer and core. The interdependent influences that have great significance in relation with the matrix are on the hand the integrity with the other materials and layers in the sandwich element. On the other hand, the durability of the element is for a large part dependent on the applied matrix, mostly because of the amount of unknowns related to this topic. Increasing the predictability of long term mechanical behaviour of engineering composites requires more research.

Although the reaction of the façade elements to fire can also be considered a part of its durability, in this case a clearer picture can be drawn when the fire behaviour of the element is assessed separately as the second key factor. The required fire behaviour of the element as a whole is an issue that puts high demands on the used polymeric compounds in the finishing layer, and in case of the state-of-the-art also on the structural layer. In contrast to the creep and fatigue behaviour, insufficient fire resistance and excessive smoke production during fire cannot be solved by increasing the stiffness and strength of the structural layer, basically over-dimensioning the mechanical properties of the element. Using each of the applicable resins, as discussed in the analysis, without any supplements, it is almost certain the sandwich element will not meet all requirements regarding its fire behaviour. Yet, additives in the polymeric compounds influence, besides properties concerning fire resistance and smoke production, also the static behaviour and durability of the entire element. Resolving this problem involves creating sufficient fire resistance, such as limiting fire spreading, smoke production, droplets and toxicity, although any regulations regarding toxicity are currently lacking, without making tremendous concessions towards the structural integrity of the separate materials and the element as a whole.

The third key factor is the production process. The type of production process is basically established, from the analysis it can be concluded that VARTM is the only logical option based on the ratio between the performance and production volume, and possibilities in shape and finish. The exact execution and circumstances of manufacturing elements with this production process are somewhat more flexible. On the one hand the design has a direct influence on the difficulty of production. On the other hand, the amount of manual labour, experience of the manpower, execution of cure and post-cure processes, and the consistency of the climate during production have a significant influence on the performance of the end-product.

The fourth and final key factor comprises the connections with the critical components, of which the most critical is the connection with the anchor system. The anisotropic nature of the structural laminate favours transferring any stresses in its plane, perpendicular to its plane composites have a much lower strength and stiffness. Default design solutions for connections with metal structures are therefore not necessarily applicable or usable for connections with an FRP composite sandwich element. The connections show more interaction with the other factors. The design of the connections can have serious implications on the production process in case complex shapes in the sandwich element are required, but also damage the sandwich element or reduce its durability at the locations where the laminate is penetrated with fasteners. Finally, the components and connections need to be capable coping with deformations due to the thermal behaviour of the composite sandwich element. Under all conditions the weather-tightness of the element needs to be guaranteed.

9.2 Optimisation in cost of design, materials and production

The height of the total costs of the entire design and production processes of monolithic FRP composite sandwich elements for unitised façade systems is currently one of the major issues, since this is considerably higher than other systems. The origin of this lies in the application of a novel material. Any unknowns during the design process need to be answered with generally expensive testing procedures, problems that arise during both the design and production process are typically countered with ad hoc found solutions. Following this course of action in a project generates a lot of additional costs and a less than optimal end-product. The costs will of course reduce when a project is started with a working concept instead of developing a working concept during a project. In this section the concept is reviewed and the results from the analysis are compared to the state-of-the-art. It must be noted that material combinations and experience with composite materials from other industries cannot be copied blindly and applied in de building industry.

9.2.1 Review of the concept

Approaching FRP composite sandwich elements as a concept with a high level of versatility, it is necessary to focus on the structure of the element, meaning the build-up of different layers, and review the functions each layer has been appointed. Reducing the number of tasks per layer to a bare minimum results in a higher flexibility and simplicity in the design. With this as a basis the tasks of each part of the sandwich element can be reviewed. The core layer functions as a thermal and sound barrier between the exterior and interior climate, and also increases the structural effectiveness of the composite layer surrounding the core. The FRP composite laminate, the structural layer of the sandwich element, is together with the core layer responsible for the structural integrity of the element and is required to provide sufficient mechanical strength, stiffness and durability during its entire life-cycle. The tasks of the finishing layer include protecting the composite laminate and core of the sandwich element from all external influences, and the responsibility for the aesthetical appearance and durability of the element.

Actually the distribution of tasks of all the layers are very similar as how this layer functions in currently applied systems, though in current systems one task is shared between the finishing layer and the composite laminate. As the material used in existing systems to form the finishing layer does not provide the entire element sufficient protection against fire, the composite laminate contains additives to increase the fire retardant properties of this layer, thereby forcing the structural layer to actively participate in the fire. There are a couple of negative consequences that come with splitting this specific task over these two layers. As the matrix is the flammable material in the composite laminate, requiring a fire retardant matrix leads to the use of more expensive matrix materials, which may demand additional attention prior to and during application. Secondly, as the fire retardant matrices are generally filled with additives such as ATH or other micro-fillers, the processability is also reduced compared to unfilled matrices. This has consequently an influence on the design of the element itself, such as the required thickness of the laminate and the maximum volume fraction of fibre reinforcement. As the finishing layer is responsible for all protective tasks and in line with keeping the flexibility of the concept, this layer should protect the substrate against fire, independent on the thickness and composition of the composite laminate, or the shape of the element in its entirety. Another positive side effect is that, with assigning the finishing layer as fire barrier, the fire behaviour of the element in its entirety is more consistent and the chance of failure during manufacturing decreases. The potential of filtration of the filler due to the fibre reinforcement or inadequate mixing of the matrix a potential failure is then also excluded from the process.

Assigning each task to a single layer of the element does lead to a more efficient and orderly designing process, which consequently might also result in a higher quality end-product and a more efficient use of materials. It must be said that, although several intumescent and char-forming mats and sprays, and fire retardant gelcoats are available, in the current situation testing is required in order to verify that a specific composition of finishing layer is up to the task of shielding the composite laminate of fire, while the quality of aesthetics and durability of the finishing layer still suffices.

9.2.2 Design for manufacturing and design for assembly

The design for manufacturing methodology can have a positive effect on the efficiency and total costs of the manufacturing process. The main idea behind this methodology is to eliminate, simplify and standardise factors during the design phase whenever this is possible, in order to optimise the entire manufacturing process. This methodology has three different aspects, namely production, assembly and support. The production aspect focuses on the production of the separate components, including the procurement and production of required tooling, such as the moulds. The second aspect focuses on the assembly of the components into the final element, and design for support focuses on overhead and support required during the manufacturing process[31].

Considering the production of the composite sandwich elements, the shape of the elements, the variety in shape and size, and the connections with the other components are the most influential factors on the costs. The shape of the elements and any variety of elements is mostly dependent on the architectural design. Potential production difficulties should therefore be resolved with this external party. It is important that both parties are aware of the fact that any variety in the façade elements lead to an immediate increase in costs. This ranges from a relative small increase, as in required additional infill-blocks for the moulds, to a large increase in costs in case additional moulds are required for production. In contrast to the overall shape of the elements, the design of the connections and the shape and size of the connection surface areas on the composite sandwich element are parts of the design that can be standardised to a large extent. Naturally the standardisation must be implemented for every type of connection separately depending on the connecting component. Here the requirements for the connection between the window and the sandwich element differ from those for the anchor construction and the sandwich element. To reduce costs it is key to keep the connections as simple as possible. It is important that the connections do not have too much influence on the final shape of the composite sandwich element, as every protrusion and crevice, and every extra edge and corner increases the difficulty of the production process. Furthermore it is easier to produce straight lines and flat surfaces than any curves in the sandwich element.

The main goal of the design for assembly methodology is to reduce the number of components and simplify the leftover connections. With the use of a monolithic element that functions as bearing structure and the closed sections this methodology is already satisfied to a great extent. Compared to other systems the assembly process of a monolithic FRP composite sandwich element based unitised façade system is considerably more efficient. As for the remaining connections and components, from the perspective of this methodology simplicity is key to minimise assembly time and costs In this case this can be interpreted as the method of connecting the components that requires the least amount of work and modification on the sandwich element is the best method[31].

9.2.3 Optimisation in production

Following the methodologies discussed above, some standard optimisations can be assessed concerning the execution of the production process. Here three optimisations are briefly discussed, namely maximising the production process cycle time, minimising labour-intensive processes and minimising process requirements. These optimisations have an immediate influence on each other. For example, process requirements, such as application of heat and high-pressure during curing, speeds up the curing process, thereby reducing the overall cycle time. Also the presence of labour-intensive processes often entails long cycle times, while replacing these processes with a simpler and faster solution may reduce the quality and durability of the end-product, or call for additional process requirements. Tools that can help find a balanced production process is the application of a process simulation and planning, with as a result an efficient production and assembly line set-up[31].

9.3 Quality, durability and other requirements

One of the issues with monolithic FRP composite sandwich elements is that only defects at the surface are immediately detectable. This includes minor and repairable issues, such as scuff marks or scratches in the finishing layer, up to hard to restore or even fatal errors, for instance delamination between layers or macro-cracks in the structural laminate. Flaws that are located deeper into the structure may appear after transport, for example due to vibrations, or even after years in service. A significant part of obtaining the desired level of quality is consistency. Production in a clean and controlled environment, with a constant temperature and relative humidity, and consistent execution of all the steps of the production process, has generally a positive contribution to the quality and durability of the end-products. In order to accurately assess the quality during production, each step of the process, both materials, equipment and the resulting sandwich elements, should be capable of being controlled, without causing any interference in the process. It must be noted that quality control during the manufacturing of FRP composites containing elements for the building industry cannot be compared to production with high-performance composites in the automotive and aerospace industries. The margins, and therefore also the budget for quality control, in the building industry are much lower compared to the other industries. This results in relative low frequency and limited inspections, and testing actual end-products solely for quality control is not an option. In order to maintain grip on the quality of the used materials and applied production process it is therefore important to follow an efficient quality assessment program including the production of small samples alongside the actual products. Quality assessment is further discussed in the third part of this thesis[16].

Although the actual quality and durability of the end-products are determined by the execution of the manufacturing and assembly processes, both are highly influenced by the design of the product. Every irregularity in the surface or cross-section of the elements, such as sharp edges and narrow spaces, creates additional difficulty to the production process and thereby increases the risk of flaws and production errors. It is therefore important to have a straightforward and error-proof design process in order to limit potential problems in a later stage of production. Starting out with a verified working concept is also a vital part of this[31].

Part II

Material Assessment

Chapter 10

Requirements for the Design and Production Processes

The basic requirements regarding the design process of monolithic FRP composite sandwich elements concern the mechanical properties of all used materials, but also the thermal properties of the structural and finishing layer. Polymer-based materials are generally much more sensitive to elevated temperatures compared to metallic or mineral-based construction materials. As for the requirements concerning the production process, these are more related to the processing behaviour of the applied materials and the necessary production steps that are required to obtain certain minimal material properties. In the end the production process has a significant influence on both the mechanical and thermal properties of the polymeric layers. As is mentioned in Chapter 1, these characteristic values are generally acquired from real-life testing or from experience. Especially testing materials over and over is a very costly process. On the other side, using data from previous experiences is very limited as these values are only applicable for a specific combination of materials in combination with a specific production process. This chapter focuses on the necessary knowns for both processes, which are required to come to a complete design, and also how the predictability of the different aspects can be improved.

10.1 Structure of monolithic FRP composite sandwich elements for unitised façade systems

Façades are one of the more diverse systems in the building industry. Buildings with more than one façade system are not even rare. For the purpose of simplification in this section unitised façade systems in combination with monolithic FRP composite sandwich are generalised to a single concept. That is, unitised systems consist in general of a square or rectangular structural framework, of which the openings are filled with infill panels or windows. Furthermore, besides the downwardly directing load of the self-weight of the element, façade elements are only subjected to one significant loading, namely the transverse oriented wind load. Applying FRP sandwich elements as the structural framework, even as the infill panels are integrated in this framework, the façade element can be seen as transverse loaded tubular sections. Though in this case it does not concern rectangular hollow sections as it would with aluminium-framed unitised façade elements. Instead the rectangular sections are filled with a rigid foam, improving the structural integrity and the rigidity of the framework.

Due to the monolithic nature of FRP composite sandwich elements, and thus the lack of relative simple connections between the mullions and transoms, the sandwich element responds more as a whole to external influences. This, and the fact that the cross-sections can have complex shapes and are filled with a different material than the structural skin is made of, increases the complexity of the necessary calculations that are required to be executed in order to verify the strength and stiffness of the element. The fact that the FRP composite material the structural skin is composed of is not an isotropic material, and also may be designed differently for different surface areas of the element, further complicates things. Therefore, there is no escape from finite element analysis (FEA) for the analysis of this kind of elements. Though, before any FEA can be executed, the mechanical and thermal material properties of the sandwich element need to be acquired. For the foam core this is rather simple since this is a homogeneous and isotropic material. The necessary material properties of the foam are normally provided by the supplier or manufacturer. As for the material properties of the composite laminate on the other hand these values prove to be more difficult to obtain. Both the mechanical and thermal properties of the laminate are dependent on the materials used and the design of the laminate, which is orthotropic at best. The following sections elaborate on the determination process of these characteristic values.

10.2 Structure of FRP composite materials

For the structural analysis of an element that is made of an isotropic material, the characteristic values of the material properties are globally applicable. For example, in case an element is produced from a specific type of steel, it has a single Young's and shear modulus, tensile, compressive and shear (yield) strengths and a single Poisson's ratio. Consequently, with these values the strength and stiffness of the entire element can be calculated. As FRP composites are not isotropic, but anisotropic, the values of these material properties can be and often are different in all directions. The properties of a composite laminate are determined by the contents of each lamina, including the form, amount, orientation and type of material of the fibre reinforcement. Normally, a lamina in a laminate consists of one ply, and a ply is defined by a single layer of fibre reinforcement. In case multiple plies are placed directly on top of each other, where each of the plies has the same fibre reinforcement with the same orientation, it can be considered a single lamina in the calculations.

FRP composite materials fall in the group of orthotropic materials, where the elastic properties of a lamina are different in three mutually perpendicular planes. The orthotropic mechanical properties of the laminae and laminates are therefore a function of the orientation. In order to determine these properties use is made of a local coordination system instead of the Cartesian coordinate system (xyz-axes system). The local coordination system used for composite materials is the principal material coordinate system (123-axes system). Here the 1-axis and 2-axis are in the plane of the composite lamina(te), the 3-axis is perpendicular to the plane of the lamina(te). The 1-axis generally runs parallel to the fibres, though this is only applicable for a single lamina with unidirectional continuous fibre reinforcement. The two coordinate systems are presented in Figure 10.1 [3] [51].

A lamina or laminate that contain continuous fibres with different orientations requires an addition to the principal material coordinate system. In this case an angle is added to the plies with respect to the 1-axis. For example, default biaxial fibre reinforcement in a lamina can be written as ⟨0°, 90°⟩. The manner of documenting this is shown in Figure 10.2. In such cases the 1-axis has the same directionality as the longest span of the element, or the directionality of the most significant stress within the element during service.

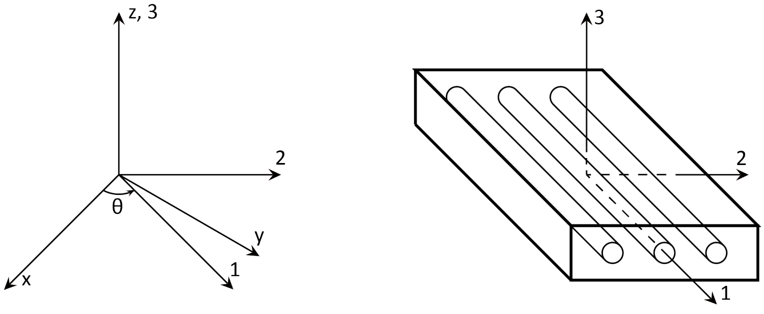

Figure 10.1: Cartesian and principal material coordinate system, and the application of the principal material coordinate system [3]

10.3 Mechanical behaviour of the elements and materials

The structural design of monolithic FRP composite sandwich elements starts with the determination of the required flexural and shear rigidity of the different parts of the element. Often the sandwich element can be divided into mullions and transoms, simplifying the design process. Subsequently the cross-section of these beams provides a set of conditions in which all the mechanical requirements must be met. The unknowns here are the thickness and lay-up of the structural laminate. A general example of a monolithic sandwich element and a cross-section of one of the beam-elements it is composed of can be seen in Figure 10.3.

In the process of the structural analysis of the monolithic sandwich elements the finishing layer is normally left out, as its contribution to the overall strength and stiffness is negligible. However, as long as the elongation at break of the polymeric compound of the finishing layer is higher than that of the structural substrate, the finishing layer keeps protecting the composite laminate up to the point of failure of the element. In the case the elongation at break of the finishing layer is smaller than that of the composite substrate, the structural skin must be over-dimensioned in order to prevent cracking of the finishing layer during the lifetime of the element.

In order to assess which mechanical properties, or engineering constants, of the used materials in the sandwich element are required to be known, the situation is even more simplified. Considered is a rectangular section, similar to the cross-section shown in Figure 10.3, which consists of a rigid foam surrounded by a stiff and strong outer shell, see Figure 10.4. Though the situation itself is simplified, the directionality of the internal stresses is still of importance due to the anisotropic

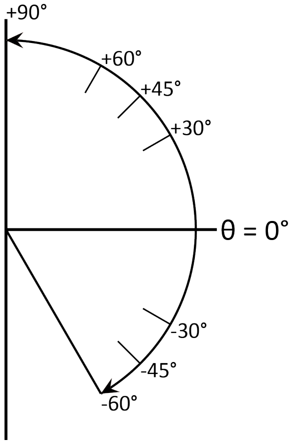

Figure 10.2: Indication of orientation of fibres in a lamina(te) [3]

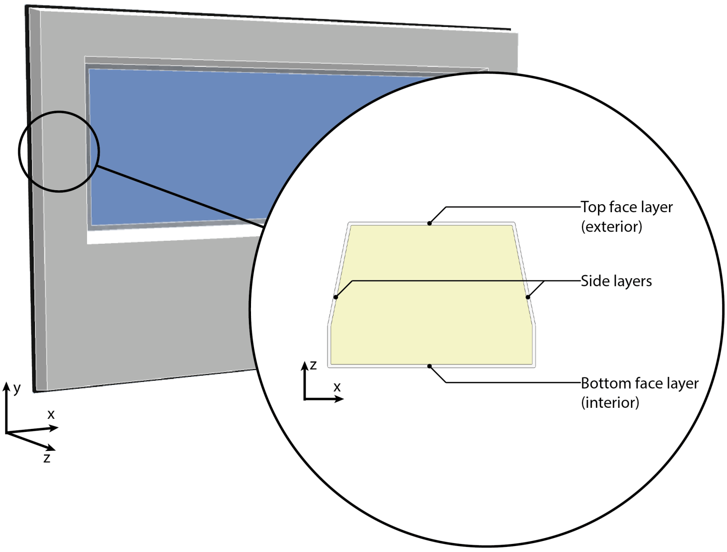
Top face layer
(exterior)
Side layers
Bottom face layer
(interior)
y
x
z
z
x

Figure 10.3: Monolithic FRP composite façade element plus cross-section of the "mullion"

nature of the FRP composite material.

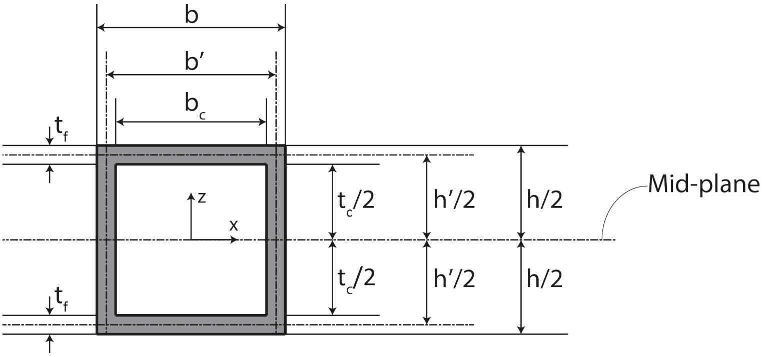
b
b′
b_c
t_f
t_f
z
x
t_c/2
t_c/2
h′/2
h′/2
h/2
h/2
Mid-plane

Figure 10.4: Cross-section tubed sandwich beam [3]

As is mentioned earlier, the only variable loading the element will be subjected to is transverse directed wind loading. The deflection of the rectangular beam-element is regulated by its flexural rigidity (D_κ) and its shear rigidity (D_γ), as is shown in the formula of Timoshenko's beam deflection theory for determining the deflection w of beams subjected to a transverse directed load F [3]:

$w = C_1 \frac{FL^4}{D_\kappa} + C_2 \frac{FL^2}{D_\gamma}$

In this formula the factors C_1 and C_2 are constants, which are depended on the type of loading. Consequently the engineering constants for tubed sandwich beam-elements can be calculated with the following formulas. Important here is that the subscript f refers to the face layers, or the outer shell, and the subscript c to the core[3].

$$D_\kappa = E_f \frac{(bh^3 - b_c h_c^3)}{12} + E_c \frac{b_c t_c^3}{12}$$

$$D_\gamma = 2h' t_f G_f + t_c b_c G_c$$

These functions show that the flexural rigidity (D_κ) is principally the sum of the tensile modulus (E) times the moment of inertia (I) of both parts of the sandwich element, and the shear rigidity is composed of the sum of the relevant surface area times the shear modulus (G). The entire surface area of the core is considered relevant, for the composite laminates only the sides are relevant.

Although, regarding monolithic sandwich elements, this method is an extremely simplified version of the reality. It does show which material properties are required to be known in advance, even when the actual calculations are done with a FEA. This simplified model and accompanying formulas show that the upper and lower face layers, that cover the interior and exterior surface of the sandwich element, transfer the transverse loading via an axial stress, while the side face layers transfer the loading via shear stress. The core transfers the loading both via axial and shear stresses. However, considering the generally low Young's modulus of rigid foams the second part of the formula describing the flexural rigidity is often considered negligible and left out of the calculations[3].

Continuing with the ends of the beam displayed in this simplified model, the transverse loads need to be transferred to the supports, or in reality via the mounting brackets of the anchor system to the bearing structure. How the stresses are transferred from the sandwich panel to the bearing structure is very much dependent on the way the mounting system is designed. The two general methods of mounting the composite sandwich elements to a building are shown in Figure 10.5.

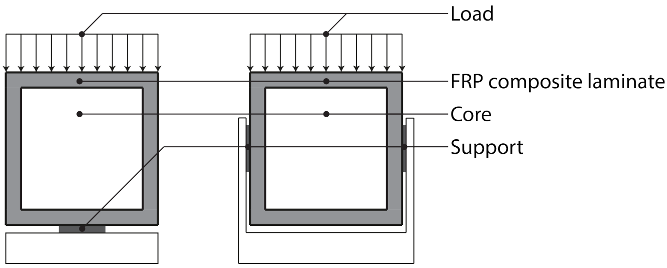

Figure 10.5: General methods of support styles

In the method shown on the left in Figure 10.5, the composite laminate in contact with the support is subjected to a transverse compressive stress. However, since the rigidity and strength of the core is much lower than that of the composite laminate, right next to the support surface area the laminate is subjected to transverse shear stress. In the second method the load on the sandwich element is transferred via the sides of the element, subjecting the composite laminate to an in-plane shear stress.

Reviewing the situation described above, the mechanical properties of the materials used that are required for further structural analysis of monolithic FRP composite sandwich elements, comprises principally all engineering constants in all directions. The only exception here is the out-of-plane tensile modulus and strength. The acquisition of the necessary values of the engineering constants is further discussed in the next section.

10.4 Determination of the mechanical properties

For building materials it is common that a standard categorisation of different grades is available, each with a specific combination of mechanical material properties. This kind of standardisation is easiest for isotropic and homogeneous materials such as steel, or for the sandwich elements the rigid foam that is used for the core material. Considering the core material, the necessary engineering constants of the specific material are normally provided by the manufacturer or the supplier. FRP composites on the other hand are extremely difficult to standardise in similar categorisations as is available for other materials. Of the default building materials, timber is the closest related to FRP composites considering the anisotropy and the large amount of different types of species, though the similarity ends there. The complexity of the possible material compositions increases due to the influences of the addition of additives, different ratios of volume fractions of all ingredients, build-up of layers with diverse fibre orientations and the applied production method.

The process of uncovering the material properties of FRP composites consists mostly of a range of physical tests, in which each test focuses on one or more specific material properties. As the composite laminate is tested with the same composition, thickness, and applied production method as is intended in the end-use, the values of the engineering constants resulting from the tests are assumed very accurate. Besides, the high level of accuracy and the low amount of tests required make this the cheapest method. Though, this method does not provide any form of flexibility. The results are only applicable for the specific material composition and laminate build-up of the tested laminate. This method is especially applicable when over long periods of time very little to no changes are required in the composite laminates used in the production of goods.

A second and somewhat more flexible option is to test each type of laminae with the preferred material compositions separately, which together form the basis for the desired laminate. When the material properties of each lamina are known, these separate properties can be combined to the material properties that are applicable for the composite laminate as a whole. The method used for this transformation is the so-called classical lamination theory (CLT). For this specific action the CLT-method is widely accepted and the method itself is not further discussed. However, the CLT-method is only a tool that combines the laminae to a single laminate, and does require the mechanical material properties of each lamina as input. This means that physical tests are still required, and as every applied lamina composition needs to be tested separately, this leads to a higher amount of tests and higher costs in comparison to the previously described method. Nevertheless, this method does allow for some variety in laminate build-ups, though it is limited to a single material combination and to the tested lamina compositions. This method is therefore ideal for businesses, which make use of a single combination of materials, but the composite laminates in the products manufactured have often different requirements concerning strength and stiffness.

The third and final option requires two crucial parts. Firstly, an extended database of basic material properties is essential, for both the fibre and matrix materials. The second part is an analytical calculation method with which all mechanical material properties of any lamina composition can be resolved, but also factors in a potential change in cohesive and adhesive properties of the matrix as additives are added to the mixture. It is expected that the necessary information is provided by the manufacturer in a technical data sheet, though information more than the axial properties, as in the Young's modulus, and tensile and compressive strength, is typically not featured. Determination of the attributes of the basic materials, such as the shear properties and the Poisson's ratios, is then left to do after purchase. Though, the challenging part of this option is the second part. The idea of an analytical method, with which the behaviour of the composite laminae can be ascertained from the basic material properties of the ingredients, is to simplify the design process with this material and render extensive test processes unnecessary. Consequently, the results can then be combined with the CLT-method in order to obtain the properties of the laminate depending on the build-up. In the past several methods have been introduced, yet between these methods there are quite some differences. To come to a unified method a lot of testing is required, with all the cost and effort that this process will entail. A couple of the existing methods are discussed in a later chapter.

Subsequently, with the CLT-method the engineering constants are determined in all three directions. A representation of the required constants is shown in Figure 10.6. FRP composite laminates are anisotropic, and from the beginning it should be assumed that none of the constants are equal, meaning for instance $E_1 \neq E_2 \neq E_3$. The same applies for all strengths (F) and all shear moduli (G). Furthermore, concerning E_1, E_2, E_3 and f_1, f_2, f_3, here the distinction must be made between these constants for tension and compression as these values are most likely not equal to each other, for example, $E_{1,t} \neq E_{1,d}$. The compressive modulus is often referred to as the bulk modulus (K), so that $E_{1,d} = K_1$. The engineering constants regarding the compressive material properties must be determined separately from the engineering constants concerning the tensile properties.

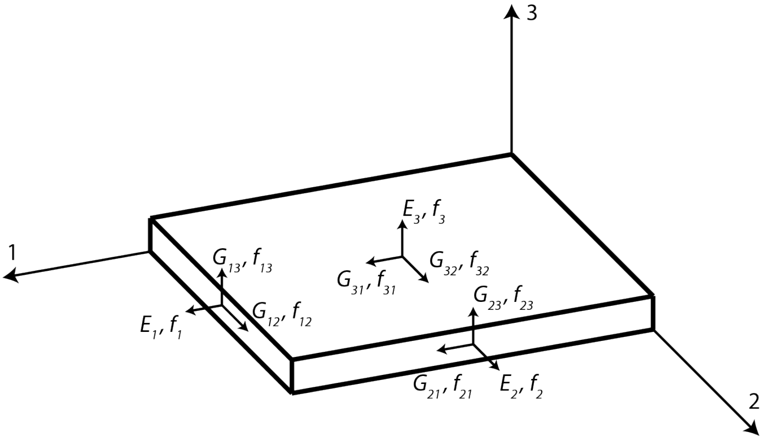

Figure 10.6: Direction dependent engineering constants of an anisotropic plate or FRP composite laminate (principal material coordinate system)

The possible tests and accompanying test standards for the determination of the engineering constants of FRP composite materials are discussed in the next chapter. Analytical methods and possibilities for the improvements in prediction of material properties of FRP composite laminae are covered in the subsequent chapters.

10.5 Thermal behaviour of the elements and materials

Principally two types of thermal behaviour need to be considered in case FRP composites are applied in façade elements, one applies to the durability of the material, the other to the mechanical behaviour in combination with temperature differences.

The first type considered is dependent on the resin that is used in the composite laminate of the sandwich element. Thermosetting resins do not melt at increased temperatures, but do soften and degrade. The maximum temperature a resin can be used in is referred to as the glass transition temperature (T_g) or the heat deflection temperature (HDT). Usage beyond this temperature results in loss in integrity of the laminate, and excessive deformations and creep behaviour. This synergistic degradation is already discussed in the analysis. The maximum temperature under which a resin may be used is regulated per country and dependent on the colour of the exterior surface area. As a safeguard in guidelines a specific value is added to the maximum temperatures, compared to which the value of T_g or HDT of the resin needs to be higher for it to be allowed to be used in that specific environment. Bright light colours applied on the exterior surface, for example white or crème, generally accedes the elements to be used in warmer climates compared to the case where darker colours are applied, such as red or black.

The second type of behaviour is thermal deflection, which basically covers the deflection of the façade element due to temperature differences between the interior and exterior environment. A safe assumption here is that the sandwich element shows a sinusoidal deformation over one axis, simply put, it shows behaviour similar to a beam. The deflection w of a sandwich beam due to temperature differences can be approximated with the following function [3]:

$w = \frac{\Delta T \alpha_f L^2}{8h'}$

Where:

ΔT	Temperature difference between interior and exterior environment
α_f	Coefficient of thermal expansion (CTE) of the FRP composite laminates
L	Span of the sandwich element
h'	Distance between the centroids of the FRP composite laminates

The CTE of the composite laminates is assumed to be mostly dependent on the volume fraction ratio of fibre and matrix material and the materials used, though the fibre orientation is of some influence. Oriented continuous fibres will reduce the deformation in the direction along the fibres. The maximum and minimum interior and exterior temperatures are determined per nation. The characteristic values, associated with the location and the applied colour on the exterior surface combined, determine if the summer or winter situation is governing. The other variables that influence the temperature inflicted deflection are related to the general design of the façade elements, the thinner the elements and the longer the span of the elements is, the greater is the temperature difference induced deflection of the elements.

The thermal behaviour of the available fibrous materials is generally speaking known information. Concerning the resin, significant more different options are available when this ingredient is compared to the fibrous material. And even when the thermal properties are supplied, in practice these properties are dependent on the production method. As soon as the production method or curing and post-curing process deviate from the overall process as is applied for the tests the manufacturer has executed, these properties are likely to different too. Ascertaining this data is done by physical testing, which is discussed in the following chapter.

Chapter 11

Material Testing Program

There is a lot of required information involved in the design process of façade elements. In order to predict the general behaviour of the sandwich elements, all the mechanical and thermal properties of the materials used in the elements must be known. For each material property a standard is available, according to which this property can be determined with a physical test. Furthermore, the elements are also designed to last for long periods, often up to 50 years. There are additional standards and test methods available for determining the durability of the applied materials. In case of the application of monolithic FRP composite sandwich elements, a lot of the features of the structural composite layer and the finishing layer need to be determined with help of physical testing. In this chapter standards are discussed that together form a complete testing program for the materials used in these two layers. Only standards of the International Organization for Standardization (ISO) and American Society for Testing and Materials (ASTM) are considered and compared briefly.

11.1 Mechanical material properties

Firstly, the determination of the mechanical properties, often referred to as the static properties, are discussed. As is explained in the previous chapter, the composite laminate in the sandwich elements can endure stress in all directions. Furthermore, the fact that in this case it does not concern a homogeneous and isotropic material, such as steel, must be taken into account. The directionality of the material in which it is tested is of influence. For isotropic materials there exists a relationship between the moduli of elasticity, meaning the tensile, bulk and shear modulus (E, G and K), and Poisson's ratio (ν), namely:

$G = \frac{E}{2(1+\nu)}$

$K = \frac{E}{3(1-2\nu)}$

For FRP composites it cannot be assumed that these relationships apply. Therefore, the execution of test concerning the tensile properties alone to determine all static properties is not sufficient, and thus the tests the determination of the compressive and shear properties of the material also need to be executed. These tests are briefly discussed in the following sections.

11.1.1 Tensile properties

The test setup for the determination of the tensile properties of a material is quite straightforward. A rod is placed in between two clamps and is subsequently pulled apart. De test standards conform which the tests need to be executed, in order for the results to be recognised and be reproducible, are ASTM D3039 or NEN-EN-ISO 527. Part 2 of ISO 527 describes the requirements for moulded plastics, including FRP composite materials.

The difference between these two test standards are the requirements of the shape of the test specimen. The ISO standard describes a dumb-bell-shaped specimen, also known as a dog bone, while the ASTM standard requires a rectangular plate with tabs placed on the ends. However, the shape of a dog bone-shaped test specimen within the ASTM standards can be derived from ASTM E8, which is meant for testing the tensile properties of metals. In both cases the cross-sectional area of the ends of the specimen, where it is mounted in the heads of the testing equipment, is increased compared to the middle section in order to force the failure of the specimen to occur in the middle and not where it is clamped in. The principle and an example of this test are shown in Figure 11.1.

Considering the production of these specimens, very little deviation is allowed in cross-sectional dimensions and overall shape in the test standards. Both the dog bone and the plate with tabs require a lot of attention during production of the specimens. As for the dog bone, in order to obtain very consistent shapes over a range of specimens, these need to be cut with a CNC machine. Deviation in the curvatures of the transitional areas of the specimen may influence the test results. Production of the rectangular test specimens according to the ASTM standard is accompanied with other difficulties. The mandatory tabs are required to have a specific shape, and subsequently four of these tabs need to be glued on the ends of each specimen. This process is quite labour intensive and requires some skill.

Testing these specimen provides results of the tensile modulus ($E_{cp;1}$), and the ultimate tensile strength ($f_{cp;1,u,t}$) and strain ($\varepsilon_{cp;1,u,t}$) of the composite laminate. The application of strain gage rosettes on each side of the specimens provides sufficient data for the determination of the Poisson's ratio ($\nu_{cp;12}$).

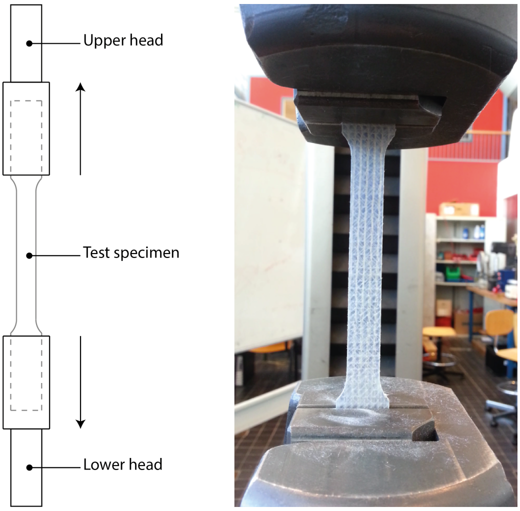

Figure 11.1: Left: Schematic representation of the tensile test setup; Right: Photo of the tensile test setup [55]

11.1.2 Compressive properties

The test setup for ascertaining the compressive properties shows some similarity with the previously discussed test setup. The with this test corresponding test standards are ASTM D3410 and NEN-EN-ISO 14126 and both test standards are principally analogous to each other. The test standards require rectangular test specimens with tabs glued on the ends. The surface area covered with tabs is much larger than without tabs, only 10 to 25 mm in the centre of the specimen is free. This way the fracturing due to compression is forced to take place in the centre of the specimen. Furthermore, by leaving a very small part of the specimen uncovered, and not clamped in, also the chance of buckling is minimised. With this test the opposite engineering constants can be obtained as with the tensile test, namely bulk modulus ($K_{cp;1}$), the ultimate compressive strength ($f_{cp;1,u,d}$) and strain ($\varepsilon_{cp;1,u,d}$) of the composite laminate.

11.1.3 Shear properties

For determining the shear properties of the composite laminate, it is important to note that here a distinction is made between in-plane shear and out-of-plane shear. First test methods relating the in-plane shear properties discussed. The only standard that is available from ISO is NEN-EN-ISO 14129, with the corresponding test standard ASTM D3518. These test standards make use of a rectangular test specimen with biaxial fibre reinforcement oriented at ±45°. In the test this specimen is loaded with tension. Subsequently the results are transformed with several calculations in to usable in-plane shear properties. This test is very limited as it is only usable for a single type of laminate composition. There are two ASTM standards that describe other test methods, which allow principally every type of composition for composite laminates, namely ASTM D4255 and ASTM D7078. The test method described by ASTM D4255 is called the rail shear method, as the rectangular plates are mounted on so-called rails, and subsequently the rails move parallel from each other, loading the specimen with a shear force. The test method of ASTM D7078 is known as the V-notched rail shear method. The specimens for this test have in the centre two V-notches, reducing the cross-sectional area of the specimen and thereby forcing the failure mode to take place in the centre of the specimen. These two test methods are shown in Figure 11.2 and Figure 11.3.

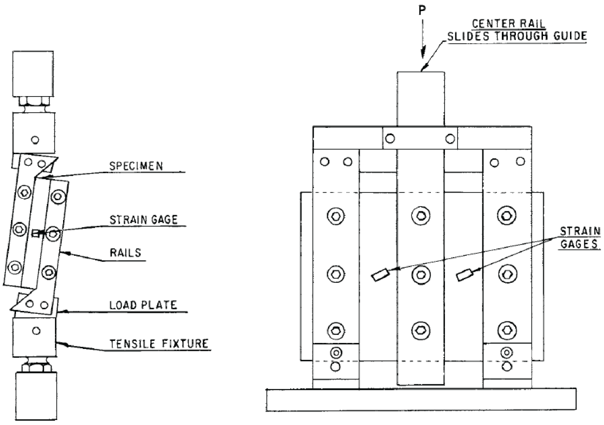

Figure 11.2: Left: Schematic representation of both in-plane shear test setups as are described by ASTM D4255

The production of the specimen for both ASTM D4255 and ASTM D7078 need to be executed with great care. Any change in cross-sectional dimension creates stress concentrations in the laminate as the specimen is loaded. The machining and finish of the holes in the specimen for the rail shear method, and the V-notches in the specimen for the other test method have a significant influence on a potential prematurely failure of the specimen due to irregularities in the edges.

With these test a number of engineering constants of the tested laminate can be determined, namely the in-plane shear modulus ($G_{cp;12}$), the ultimate in-plane shear strength ($f_{cp;12,u,V}$), and the ultimate in-plane shear strain ($\varepsilon_{cp;12,u,V}$) or engineering shear strain ($\gamma_{cp;12}$)

For the determination of the out-of-plane shear properties small rectangular specimens are tested with a three-point bending test, as is described by the test stan-

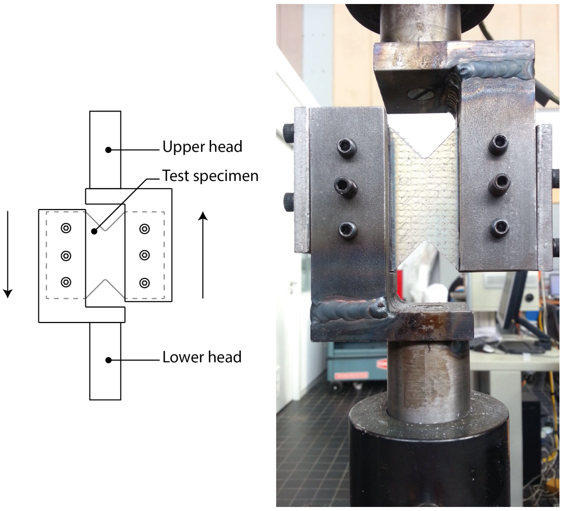

Figure 11.3: Left: Schematic representation of the in-plane shear test setup as is described by ASTM D7078; Right: Photo of the in-plane shear test setup [55]

dards NEN-EN-ISO 14130 and ASTM D2344. The ISO standard prescribes a test specimen with the dimensions 20 × 10 × 2 [mm] (L×W×H). The ASTM standard is somewhat more flexible. Here the length of the specimen needs to be six times the thickness, the width needs to be two times the thickness. It must be noted that both these test standards are only used for the determination of the apparent interlaminar shear strength ($f_{cp;13,u,V}$). The out-of-plane shear modulus ($G_{cp;13}$) can only be approximated by processing the measured results, for example by applying Timoshenko's beam theory, but this is not discussed nor corroborated in either of the standards.

11.2 Thermal material properties

Not only the static behaviour of FRP composites is important to know during the design phase, also its thermal behaviour can play a significant role. In this section the required engineering constants and corresponding test methods are briefly discussed.

11.2.1 Coefficient of thermal expansion (CTE)

The test methods for determination of the CTE of the to be tested specimens are provided by NEN-ISO 11359 and ASTM D696. This constant is determined by testing the specimen in an enclosed environment under at a constant rate varying temperatures. According to the ASTM standard the material needs to be tested between -30 °C and 30 °C, the ISO standard prescribes a range from at least 50 °C below and above the glass transition temperature (T_g) of the specimen.

11.2.2 Maximum in-use temperature

In practice there are two engineering constants that are used to describe the maximum continuous-use temperature of a plastic, both thermosetting and thermoplastic, namely the glass transition temperature (T_g) and the heat deflection temperature (HDT). This is also assumed applicable to FRP composite materials. However, both constants are used interchangeably without any restriction, while the test methods, and therefore also the results, are not the same. Generally the test method for determining the HDT is easier to execute and the necessary equipment is less expensive in purchase and use, but the test methods providing the T_g are more accurate, and the results of this test method are often higher than the results of the test providing the HDT.

The HDT can be determined with the test standards NEN-EN-ISO 75 and ASTM D648. Both standards describe principally the same test setup, a small specimen is placed in a bath of which the fluid is heated up with about 2 °C per minute. The specimen itself is placed in a three-point bending test under a constant load. At some point the specimen softens due to the heated up environment, which causes the specimen to deflect increasingly. At a certain deflection it is considered that the specimen has failed, and that temperature is the HDT.

The glass transition temperature can be determined by a multiple test methods, namely with dynamic mechanical analysis (DMA), according to test standards NEN-EN-ISO 6721 and ASTM D7028, or with differential scanning calorimetry (DSC), as is described in the corresponding test standards NEN-EN-ISO 11357 and ASTM D7426. With the application of DMA the specimen is loaded in flexure, the loading occurs dynamically at a specific frequency, while the enclosed environment, in which the specimen is located, is heated up. With DSC the specimen is not loaded, but the heat flow difference between the specimen and a reference is measured. For determining the T_g is often referred to the application of DMA.

11.3 Material durability features

The durability of composite materials is dominated by its behaviour towards time-dependent influences. Mechanically this concerns the creep and fatigue behaviour of the laminate. Testing composite materials on creep is described in the test standards NEN-EN-ISO 899 and ASTM D2990. In principle the tests provided by the standards cover a number of tests where the specimens are subjected to a constant load. Consequently, the specimens are expected to extent continuously and this behaviour needs to be measured at predetermined intervals. The ASTM standard prescribes test methods for determining the tensile, compressive and flexural creep behaviour of the to be tested material, the ISO standard only covers the tensile and flexural creep behaviour. Tensile and compressive creep is tested with similar test setups as are meant for determining the static tensile behaviour of the material. Flexural creep requires a three-point bending test setup, although the ASTM standard also allows the application of the four-point bending test setup.

The fatigue properties of FRP composite materials can be determined with test standards ASTM D7791 and D7774, and NEN-ISO 13003. ASTM D7791 describes a test method for the tensile and compressive fatigue properties of plastics, ASTM D7774 covers the flexural fatigue properties. Test methods for the determination of tensile and flexural fatigue properties of FRP reinforced materials are both discussed in NEN-ISO 13003. The tests are executed in similar test setups as are described above regarding the determination of the creep properties, only here the specimens are subjected to a cyclic loading. The size and shape of the test specimens for these test methods is in accordance with the size and shape as is described in the test standards for the determination of the static tensile, compressive and flexural material properties.

Another long-term influence on the laminate is weathering. The influence of weathering is mostly applicable on the finishing layer. For these tests the specimens consist of a piece of laminate with finishing layer, and the side with the finishing layer is exposed to the influences of the test environment. The influence of weathering is tested in enclosed environments in which the side with the finishing is subjected to UV light and moisture. These tests intend to reproduce the effects of sunlight and rain. The weathering can be tested in accordance to two different methods. In the first method the specimens are exposed to fluorescent ultraviolet (UV) radiation, as is described by test standards NEN-EN-ISO 11507 and ASTM G154. The second method makes use of exposure to filtered xenon-arc radiation, of which the test methods are provided by NEN-EN-ISO 11341 and ASTM G155. For both methods the ASTM and ISO standards are practically the same.

11.4 Brief review of the test standards

The sections above show that a lot of different tests need to be executed in order to be able to design elements with FRP composites, Table 11.1 provides an overview of the applicable test standards.

When the ASTM and ISO standards are compared to each other, it can be concluded that the methods described in the standards are principally the same, or at least show great similarity. In some cases there are only slight differences present, often related to the required dimensions of the test specimens. However, the build-

Table 11.1: Overview of applicable test standards

	Test standards	
	ASTM	ISO
Mechanical behaviour		
Tensile properties	ASTM D3039	NEN-EN-ISO 527
Compressive properties	ASTM D3410	NEN-EN-ISO 14126
Shear Properties (in-plane)	ASTM D3518 ASTM D4255 ASTM D7078	NEN-EN-ISO 14129
Shear Properties (out-of-plane)	ASTM D2344	NEN-EN-ISO 14130
Thermal behaviour		
Thermal expansion	ASTM D696	NEN-ISO 11359
Max. in-use temperature (HDT)	ASTM D648	NEN-EN-ISO 75
Max. in-use temperature (T_g, DMA)	ASTM D7028	NEN-EN-ISO 6721
Max. in-use temperature (T_g, DSC)	ASTM D7426	NEN-EN-ISO 11357
Durability		
Creep behaviour	ASTM D2990	NEN-EN-ISO 899
Fatigue behaviour	ASTM D7791 ASTM D7774	NEN-ISO 13003
Weathering	ASTM G154 ASTM G155	NEN-EN-ISO 11507 NEN-EN-ISO 11341

up of the documents provided by both organisations is show a significant amount of differences. The most obvious one is that for the determination of a single set of properties, for example the tensile properties of a material, the test method provided by the ASTM is described concise and clear in a single document, while in comparison the ISO often supplies multiple documents of which the content is extensive, often vague and exists for a large part of cross-references to other documents. Considering the level of usability and user-friendly content of the documents, and furthermore the global application of the ASTM standards versus the European application of the ISO standards, makes the preferred choice for a complete test program one that is based on ASTM standards.

Chapter 12

Possibilities in Prediction of the Static Behaviour of FRP Composites

The design and production of monolithic FRP composite sandwich elements for unitised façade systems require the application of advanced laminate designs, meaning, the application of solely random fibre reinforcement is assumed to be insufficient. The stiffness and strength of the laminates are for the largest part provided by oriented continuous fibre reinforcement. Obtaining the necessary engineering constants of an FRP composite laminate with a specific composition is normally accomplished by performing the various tests that are described in the previous chapter. For this range of materials, this is actually a standard procedure. There is not a unified and verified analytical method available, which would make these tests to a large extent unnecessary. Initially, the development of such a method requires substantial amount of resources, but in the long run it will save time and money due to an easier and accelerated design process. In this chapter a couple of existing analytical methods are reviewed and additional possibilities are examined in improving prediction of the failure modes of FRP composites. This analysis is compared to and substantiated with test results that have been executed parallel to this research[55].

12.1 Calculation methods for FRP composite materials

Most analytical methods were developed for composites that were meant for other industries than the building industry, mostly for aerospace applications. FRP composite structures in the aerospace industry are all made of high-performance composites, where principally all fibre reinforcement consists of oriented continuous fibres. Also, the main focus within these methods is the determination of the various moduli of the FRP composite laminae. Very little research can be found when it comes to broadly substantiated calculation methods for the determination of the various strengths of FRP composites. In the following sections three much used analytical calculation methods are compared to data resulting from tests with engineering composites and to each other, namely the Rule of mixtures (RoM), the Halpin-Tsai method (H-T), and the Chamis equations (CE)[3].

12.1.1 Tensile moduli

As input for the analysis of the calculation methods, some material properties are taken over from the tensile tests that are used as reference. Considering the matrix, it is assumed that the matrix has a tensile modulus of $E_{mx} = 2.86 \cdot 10^3$ N/mm^2 and a Poisson's ratio of $\nu_{mx} = 0.41$. The same engineering constants for the fibrous material are presumed to be $E_{fr} = 72.3 \cdot 10^3$ N/mm^2 and $\nu_{mx} = 0.22$. Considering a composite lamina with unidirectional fibre reinforcement oriented at +0°, all three methods agree about the formula with which the tensile modulus in the 1-direction can be determined, namely[3] [55]:

$E_{cp;1} = E_{fr}v_{fr} + E_{mx}v_{mx}$

Filling in the material properties in this formula, it can be plotted against the results for the physical tests. This is shown in Figure 12.1. The results of the three sets in this graph are of test specimens with unidirectional fibre reinforcement oriented at +0°.

It shows that this method is rather accurate, although it cannot be said that it is a conservative method. Some of the results are lower than should have been according to the analytical method.

For the calculation of the tensile modulus in the 2-direction, each of the methods describes its own formula. The formula according to the Rule of mixtures is[3]:

$E_{cp;2} = \frac{E_{fr}E_{mx}}{E_{fr}v_{mx}+E_{mx}v_{fr}}$

Halpin-Tsai prescribes a somewhat more complex function, namely[3]:

$E_{cp;2} = E_{mx}(\frac{1+\xi\eta v_{fr}}{1-\eta v_{fr}}), \eta = \frac{M_R-1}{M_R+\xi}, M_R = \frac{E_{fr}}{E_{mx}}, \xi = 2$

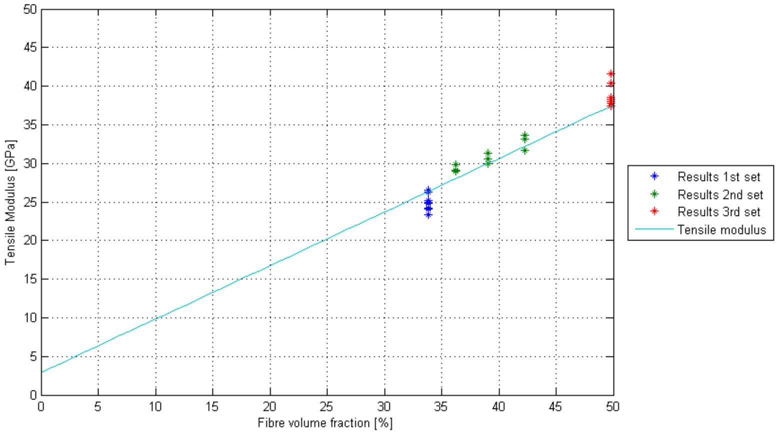

Figure 12.1: Analytical determination of the tensile modulus in the 1-direction ($E_{cp;1}$) versus measured results of specimen containing unidirectional fibre reinforcement oriented at +0° [55]

And finally, the tensile modulus in the 2-direction according to the Chamis equations is[3]:

$$E_{cp;2} = \frac{E_{mx}}{1-\sqrt{v_{fr}}(1-\frac{E_{mx}}{E_{fr}})}$$

These three formulas are plotted against the results of the three sets of test specimens containing unidirectional fibre reinforcement oriented at +90°, as can be seen in Figure 12.2. According to this graph it appears that compared to the test results all three methods can be considered conservative.

The discussed methods do not provide a formula that determines the tensile moduli of laminae containing unidirectional fibre reinforcement oriented at ±45°. However, results from tensile tests of specimens with this type of fibre reinforcement have shown that this fibre orientation causes the laminae to have a lower tensile modulus ($E_{cp;1}$) than when the fibres are oriented at +90° with respect to the directionality of the tensile stress. Interestingly, plotting the results of these tests with the formulas with which the tensile modulus in the 2-direction can be determined, the formulas that are previously used for the determination of $E_{cp;2}$, shows that the formula provided by the Rule of mixtures can still be considered conservative, while the formulas provided by the other two methods show great similarity with the test results, as is demonstrated by Figure 12.3. It might be possible that these formulas can be used to determine indicative or even characteristic values for all tensile moduli of off-axes loaded composite laminae containing unidirectional fibre reinforcement, especially in case of the Rule of mixtures as this results in moderate to very conservative values. Verification of this solution requires more testing, where the fibre orientation is the main variable.

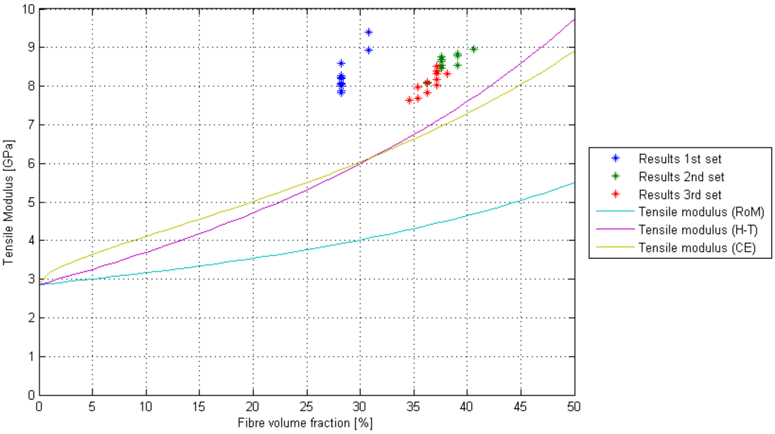

Figure 12.2: Analytical determination of the tensile modulus in the 2-direction ($E_{cp;2}$) versus measured results of specimen containing unidirectional fibre reinforcement oriented at +90° [55]

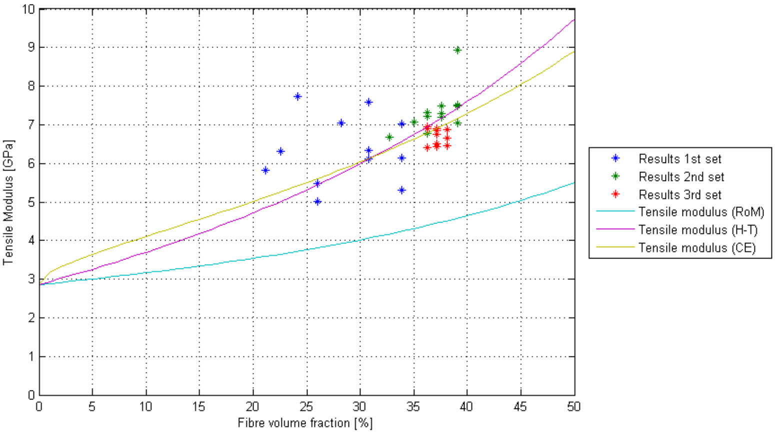

Figure 12.3: Analytical determination of the tensile modulus in the 1-direction ($E_{cp;1}$) versus measured results of specimen containing unidirectional fibre reinforcement oriented at +45° [55]

12.1.2 Shear moduli

The input for the comparison of the by the calculation methods provided formulas, which describe the shear moduli, and applicable test results, again a number of material properties are taken over from the in-plane and out-of-plane shear tests that are used as reference. Here it concerns the engineering constants $G_{fr} = 29.6 \cdot 10^3$ N/mm^2, $G_{mx;12} = 1.86 \cdot 10^3$ N/mm^2 and $G_{mx;23} = 0.29 \cdot 10^3$ N/mm^2. The first formula originates from the Rule of mixtures, and is similar to the determination of the tensile modulus in the 2-direction[3]:

$$G_{cp;12} = \frac{G_{fr}G_{mx}}{G_{fr}v_{mx}+G_{mx}v_{fr}}$$

Next, the in-plane shear modulus can be determined with the Halpin-Tsai method as follows[3]:

$$G_{cp;12} = G_{mx;12}\left(\frac{1+\xi\eta v_{fr}}{1-\eta v_{fr}}\right), \eta = \frac{M_R-1}{M_R+\xi}, M_R = \frac{G_{fr}}{G_{mx;12}}, \xi = 1$$

And finally, the Chamis equations describe the determination of the in-plane shear modulus with the following formula[3]:

$$G_{cp;12} = \frac{G_{mx;12}}{1-\sqrt{v_{fr}}(1-\frac{G_{mx}}{G_{fr}})}$$

These three formulas are plotted against test results from unidirectional (+0°) fibre reinforced specimens, as is shown in Figure 12.4. Here it must be noted that in the research the results of the second set are presumed to be the most reliable.

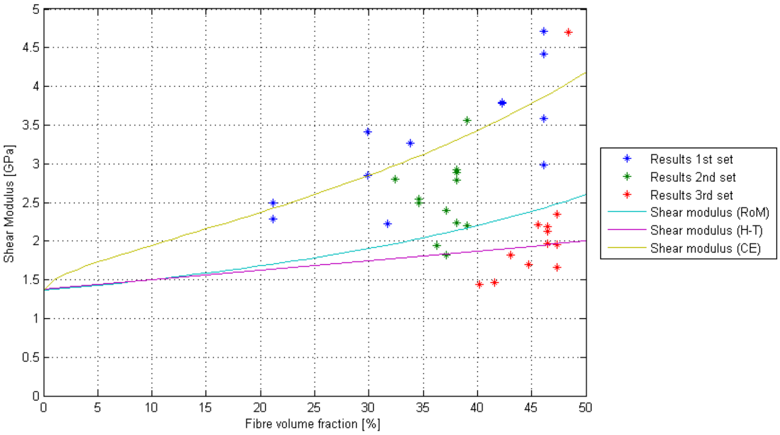

Figure 12.4: Analytical determination of the in-plane shear modulus in the 12-direction ($G_{cp;12}$) versus measured results of specimen containing unidirectional fibre reinforcement oriented at +0° [55]

Between the plots of the three formulas, an area is covered in which a substantial part of the test results are located. Assessing the situation more closely it appears that in accordance with these results, the formulas provided by the Rule of mixtures and the Halpin-Tsai method are most accurate, although the considerable amount of scatter in the results make it difficult to give a useful evaluation of the situation.

Besides the in-plane shear modulus it is convenient for the design process to be able to easily determine the out-of-plane shear modulus. The Rule of mixtures does not provide a specific formula for this engineering constant, but the Halpin-Tsai method and the Chamis equations do. The associated formulas are respectively[3]:

$$G_{cp;13} = G_{mx;13}(\frac{1+\xi\eta v_{fr}}{1-\eta v_{fr}}), \eta = \frac{M_R-1}{M_R+\xi}, M_R = \frac{G_{fr}}{G_{mx;13}}, \xi = \frac{1+v_{mx}}{3-v_{mx}-4v_{mx}^2}$$

and:

$$G_{cp;13} = \frac{G_{mx;13}}{1-\sqrt{v_{fr}}(1-\frac{G_{mx;13}}{G_{fr}})}$$

Overall, the formula provided by the Halpin-Tsai method for determining the out-of-plane shear modulus is practically unwieldy, especially compared to the expression described by the Chamis equations. Both formulas are plotted against results of tested specimens with unidirectional fibre reinforcement, as is shown in Figure 12.5.

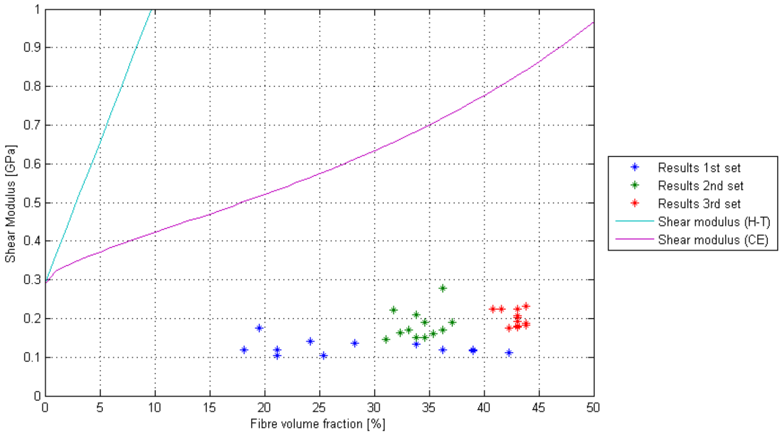

Figure 12.5: Analytical determination of the out-of-plane shear modulus in the 12-direction ($G_{cp;23}$) versus measured results of specimen containing unidirectional fibre reinforcement oriented at +0° [55]

The graph shown in Figure 12.5 can only lead to one conclusion, and that is that both of these methods do not agree with the measures values. The test results even indicate that the fibre reinforcement has a negative contribution to the out-of-plane shear modulus, while both methods assume a positive contribution. In the study the test results are derived from, it is stated that the determination method of this engineering constant is not designed for this application. This may be the cause of these large differences between the analytical methods and the measured values[55].

12.1.3 Poisson's ratios

All three discussed methods do not only agree on the determination of the longitudinal tensile modulus ($E_{cp;1}$) of unidirectional fibre reinforced laminae, but also on the required formula for calculating the major Poisson's ratio of composite laminae. This generally accepted formula is:

$\nu_{cp;12} = \nu_{fr} v_{fr} + \nu_{mx} v_{mx}$

The accuracy and reliability of this formula can be assumed to be sufficient, since it is prescribed in each of the calculation methods. However, the tests that have been executed parallel to this research do not contain sufficient results of the Poisson's ratios of the tested specimens in order to verify this formula, and is therefore not further discussed.

12.1.4 Conversion of the moduli

It is mentioned before that there are not really methods available for determining off-axis moduli, except for $E_{cp;2}$. These methods are not developed for the case of laminae containing fibre reinforcement with orientations at an angle between +0° and +90°. By applying a transformation matrix on the stiffness matrix the following conversion formulas can be derived for $E_{cp;x}$, $E_{cp;y}$ and $G_{cp;xy}$ [3]:

$E_x = (\frac{m^4}{E_1} + (\frac{1}{G_{12}} - \frac{2\nu_{12}}{E_1})m^2n^2 + \frac{n^4}{E_2})^{-1}$

$E_y = (\frac{n^4}{E_1} + (\frac{1}{G_{12}} - \frac{2\nu_{12}}{E_1})m^2n^2 + \frac{m^4}{E_2})^{-1}$

$G_{xy} = (2m^2n^2((\frac{2}{E_1} + \frac{2}{E_2} + \frac{4\nu_{12}}{E_1} - \frac{1}{G_{12}}) + \frac{n^4+m^4}{G_{12}}))^{-1}$

With:
$m = cos\theta$
$n = sin\theta$

Subsequently, the formulas provided by the calculation methods Rule of mixtures (RoM), Halpin-Tsai (H-T) and Chamis equations (CE), can serve as input for the engineering constants E_1, E_2, G_{12} and ν_{12}, which are all also dependent on the fibre volume fraction. The next step is to compare the converted moduli of the calculation methods with the results of specimens that contain fibres oriented at ±45° relative to the 1-axis. The plots and test results regarding the tensile modulus are displayed next to each other in Figure 12.6, the plots and test results regarding the shear modulus are displayed in Figure 12.8 and Figure 12.9.

Applying the conversion formula in order to determine the tensile modulus of laminae with the fibres orientated at ±45°, quite accurate results can be achieved when the Rule of mixtures or Halpin-Tsai is used as basis. These results can be even considered conservative compared to these test results. The engineering

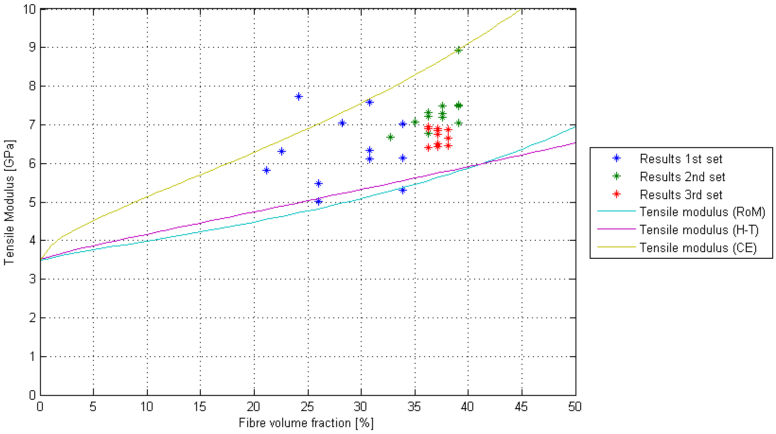

Figure 12.6: Comparison with a for 45° conversed tensile moduli ($E_{cp;x}$) versus measured results of specimen containing unidirectional fibre reinforcement oriented at +45° [55]

constants determined with the Chamis equations cause rather optimistic results in combination with the conversion formula.

In case a composite lamina is loaded with a shear force, it is important whether the orientation of the fibres is +45° or -45° relative to the 1-axis. As can be seen in Figure 12.7 in the example on the left, the fibres are actually loaded longitudinally, comparable to fibres oriented at +0° loaded with a tension force. In the example on the right the fibres are subject to a load transverse to the fibre orientation, causing the fibres to be pulled apart.

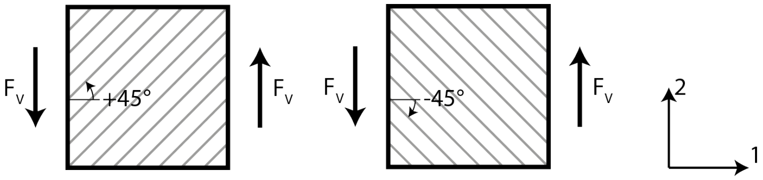

Figure 12.7: Lamina with unidirectional fibre reinforcement oriented at +45° (left) and -45° (right), both loaded subjected to a shear force F_V

This distinction is also made with the test results, but the conversion formula does not take this into account. This is because the stiffness matrix is principally meant for isotropic materials and therefore not necessarily applicable for composite laminates. The effects show itself in Figure 12.8 and Figure 12.9.

Surprisingly, the conversion based on the Rule of mixtures provides the most accurate results for the laminates with fibres oriented in the +45° direction relative to the results of the second set shown in this graph. It must be noted that the

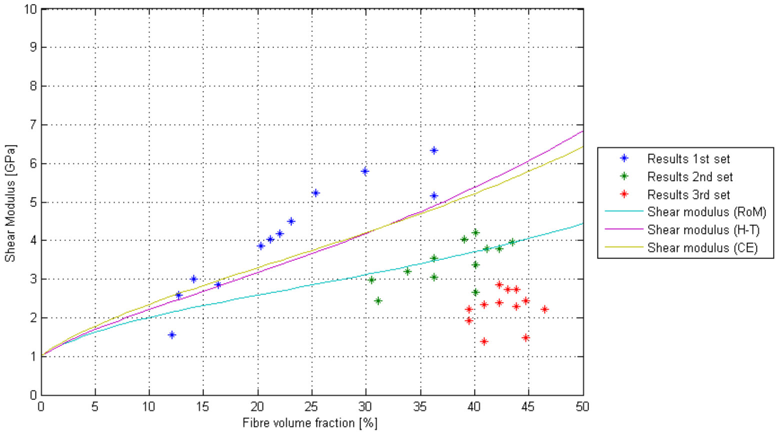

Figure 12.8: Comparison with a for 45° conversed shear moduli ($G_{cp;xy}$) versus measured results of specimen containing unidirectional fibre reinforcement oriented at +45° [55]

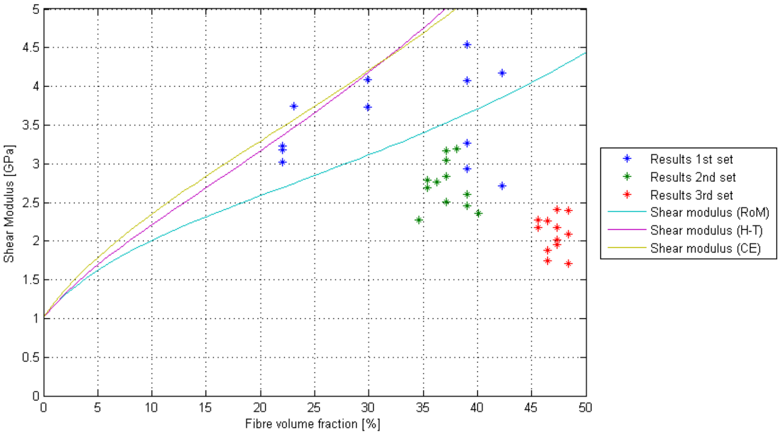

Figure 12.9: Comparison with a for 45° conversed shear moduli ($G_{cp;xy}$) versus measured results of specimen containing unidirectional fibre reinforcement oriented at -45° [55]

research, which the test results are part of, makes notion that the second set provided the most reliable results, as the specimens of the first set showed signs of buckling and the specimens of the third set were subject to substantial slipping during the tests. The conversions based on Halpin-Tsai and the Chamis equations present for this type of laminate already a fairly optimistic curve.

As for the specimens with the unidirectional fibre reinforcement oriented at -45° all three methods produce too optimistic results compared to the measured results.

The results of the test specimen are hinting at a decrease in stiffness as the fibre content increases, but the curves provided by the three different methods all have a positive slope. This implicates that for this type of laminate the aforementioned conversion formula is most likely not applicable for this combination of loading and lamina composition.

12.1.5 Tensile and shear strengths

The Halpin-Tsai method and Chamis equations are generally only applicable for the determination of the moduli of composite laminae, calculation of tensile, compressive or shear strength is principally disregarded. It does occur that the formulas provided by the Rule of mixtures are used to determine the strength of composite materials. In that case the following formulas are used and consequently are here compared to test results of tensile and in-plane shear loaded test specimens. As input some engineering constants are taken over from the corresponding research, namely $f_{fr;u,t} = 3445$ N/mm^2, $f_{mx;u,t} = 46.54$ N/mm^2, $f_{fr;u,V} = 1988$ N/mm^2 and $f_{mx;u,V} = 24.68$ N/mm^2 [55].

$$f_{cp;1,u,t} = f_{fr;u,t}v_{fr} + f_{mx;u,t}v_{mx}$$

$$f_{cp;2,u,t} = \frac{f_{fr;u,t}f_{mx;u,t}}{f_{fr;u,t}v_{mx}+f_{mx;u,t}v_{fr}}$$

$$f_{cp;12,u,V} = \frac{f_{fr;u,V}f_{mx;u,V}}{f_{fr;u,V}v_{mx}+f_{mx;u,V}v_{fr}}$$

The graphs in which these formulas are plotted and are compared to the corresponding results of the tested specimens, are shown in respectively Figure 12.10, Figure 12.11 and Figure 12.12.

Figure 12.10 and Figure 12.11 show that this method of estimating the tensile strengths of a unidirectional fibre reinforced lamina is not at all suitable. The values determined with the Rule of mixtures describe a perfect situation, which principally cannot be reached with FRP composites. Regarding the measured values of strength in the specimens with unidirectional fibre reinforcement oriented at +90°, as is shown in Figure 12.11, the fibre reinforcement appears to have barely a positive result on the strength of the lamina, often it even has a negative contribution. Also this formula is not in correspondence with the test results.

Remarkably, applying the aforementioned formula to determine the in-plane shear strength ($f_{cp;12,u,V}$) of unidirectional fibre reinforced laminae, of which the fibres are oriented at +0°, shows that this formula produces a curve that approximates the test results. By far the most test results are located just above the to the formula corresponding curve, but further testing is required to prove its usefulness.

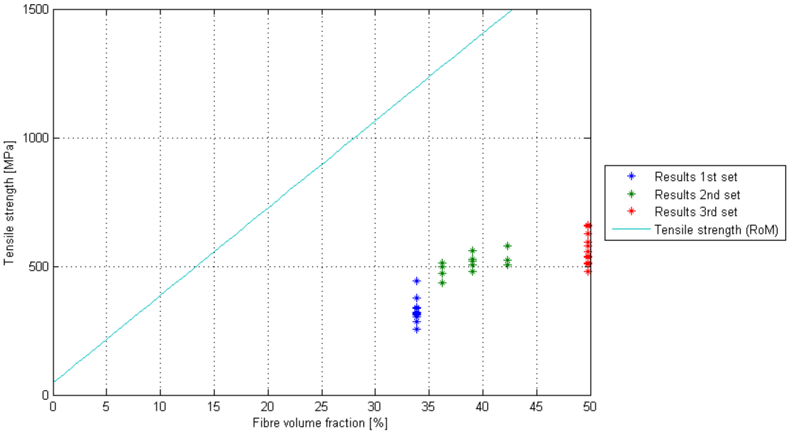

Figure 12.10: Analytical determination of the tensile strength in the 1-direction ($f_{cp;1,u,t}$) versus measured results of specimen containing unidirectional fibre reinforcement oriented at $+0^{\circ}$ [55]

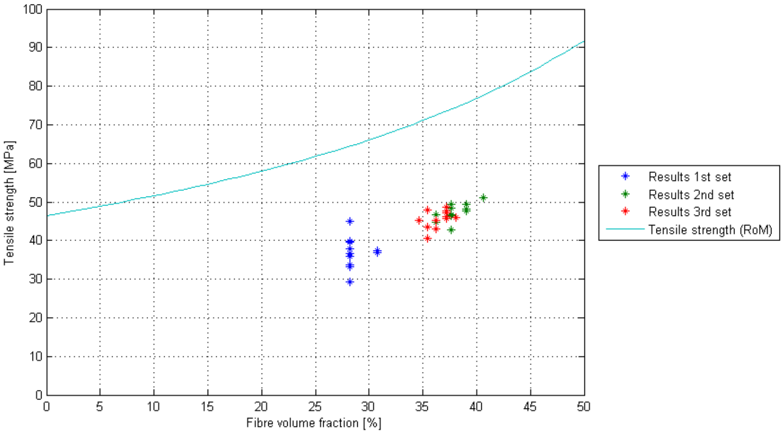

Figure 12.11: Analytical determination of the tensile strength in the 2-direction ($f_{cp;2,u,t}$) versus measured results of specimen containing unidirectional fibre reinforcement oriented at $+90^{\circ}$ [55]

12.2 Brief discussion of the analysed calculation methods

The purpose of developing and verifying calculation methods with which all properties of the composite laminae can be determined, is to remove expensive and

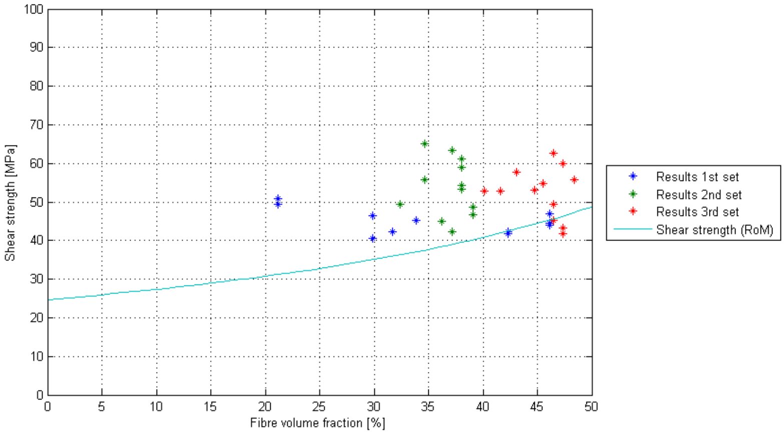

Figure 12.12: Analytical determination of the shear strength in the 12-direction ($f_{cp;12,u,V}$) versus measured results of specimen containing unidirectional fibre reinforcement oriented at $+0°$ [55]

time consuming testing programs gradually from the design and production process. The current situation regarding the availability, accuracy and reliability of such analytical methods is still uncertain, especially for the building industry applicable engineering composites. Furthermore, the comparison between the by the methods provided formulas and actual test results, it is made clear that determination methods for the strengths are far less developed compared to what is available for ascertaining the various moduli. The fact that the calculation methods for a large part ignore ways to predict the strengths of composites hints at the possibility that the moduli of FRP composites are more accurately predictable, and looking at the test results it is clear that the scatter in the results of the strengths is often greater than in the results of the corresponding stiffness [55].

Recalling the plots of the calculation methods and the related test results, shown in Figure 12.1 up to Figure 12.12, it is clear that for the approximation of the tensile and shear moduli the assessed methods are adequate, with exception of the out-of-plane shear modulus. The method that displayed generally the highest accuracy regarding the moduli is the Halpin-Tsai method. Considering the conversion of the methods for evaluating laminae with unidirectional fibre reinforcement oriented at ±45°, the Rule of mixtures provided the best results. As for determining the strength of a lamina, this process requires significant advances in research before a usable solution is developed. The current method provided by the Rule of mixtures returns excessively high values for the tensile strengths compared to the test results. It must be considered that these large differences are not solely caused by the inaccuracy of the calculation method. Irregularities and contaminations within the specimens can have a tremendous negative influence on the integrity of composite materials, resulting in relative low stresses at the moment of failure. On the other hand, this same method supplies unexpectedly accurate results concerning the approximation of in-plane shear strengths.

Knowing to what degree these calculation methods apply on the moduli and strengths of engineering composites, similar to the tested specimens with which these methods are compared, does allow for improvements in the design process. A significant amount of necessary engineering constants can be predicted with reasonable accuracy. Though, these need to be considered as indicative values and not actual characteristic material properties. It is strongly advised that the definitive static behaviour of the final design of the laminate still is verified with physical tests.

12.3 Prognoses of failure modes of laminae

Part of improving the predictability of the behaviour of FRP composite materials is assessing the weak spots in the composite laminate and the sandwich element as a whole. Normally this can be relatively easily done by executing a finite element analysis, and subsequently locate the areas with stress concentrations. Though, considering the fact that FRP composites are anisotropic this method is only partially applicable. It is for composites true that the probability of failure is the highest at the smallest cross-sectional area or other stress concentrations, but the actual origin of failure and subsequent fracture pattern may be located elsewhere. Any irregularities around edges and contaminations in the matrix are also able to initiate fracturing. Regarding laminae with continuous oriented fibre reinforcement it is important to know that fracturing of the lamina follows the fibres. Thereby considering that the matrix is by far the weakest part of the composite, as soon as the stress in the lamina is not parallel to the fibre orientation, the matrix is automatically loaded with tensile and/or shear stresses that eventually tear the lamina apart. This behaviour can also occur in places where the fibres are locally interrupted and at locations where changes in the cross-section take place[55].

Preventing premature failure of the composite laminate can be achieved in multiple ways. Firstly, it is important that at the locations where stress concentrations occur the laminate is provided with sufficient integrity, for example by applying quadraxial fibre reinforcement. Furthermore, the performance of the laminate is improved in case a balanced build-up of laminae is applied. This prevents undesired deformations of the laminate during curing, also known as warping of the laminate, and when it is loaded[48] [55].

Part III

Quality Assurance

Chapter 13

A Brief Introduction into Quality Assurance

In brief quality assurance (QA) is comprised of a collection of processes and activities that are carried out in order to ensure the end-products meet the predefined requirements, in other words to guarantee a minimum level of quality. Furthermore, with the application of a QA-program it is also possible to detect potential errors in the production process. It is therefore of importance that the program covers each step of the production and assembly process, and thereby also the used materials and components, without interfering in or slowing down production. This results in to specific situation tailored processes or activities, making each QA-program principally bespoke work. The fundamentals concerning the guidelines for compiling a QA-program are described in test standards, such as ISO 9000.

Regarding the production of monolithic FRP composite elements, the main objective of the application of a QA-program here is to reduce the failure costs and prevent faulty elements to be delivered and installed on site. The following chapters discuss failure of the sandwich elements, and how the quality of the materials and production process can be assessed.

Chapter 14

Failure Modes and Causes of FRP Composite Material Containing Elements

As with all products FRP composite sandwich façade elements can fail during production or during service life. The causes of the failures can be divided into three groups, namely design-related, production-related and material-related failure causes.

14.1 Failure causes

Façade elements, or structural elements in general, can show defects for several reasons. For instance, parts of the element can be damaged or missing, the element does not meet the performance specifications, the element shows inconsistencies due to misalignment or nonconformity, or the physical appearance of the element is not according to the design specifications. As is mentioned above these defects have their origin in the design process, production process or the materials used for the manufacturing of the element[31].

The design process has a lot of influence on the amount of and chance on potential failures of the elements. The choices that are made during the design process can cause difficulties or defects in the later stages. For example, tight spaces, complex shapes and small tolerances can make the fabrication and assembly of the element very difficult or even impossible. Furthermore, the choice in raw materials has a large impact on the production process, the overall performance and durability of the element. Besides this, matters such as shrinkage of the composite material during cure needs to be taken into account during the design process. Ignoring certain properties, behaviour and interaction of the materials, are the main cause of production failures, misalignment, nonconformity and reduced durability. Finally, during the design process it is also important to take the serviceability of the elements into account[14] [31].

Defects introduced purely by the production process generally have impact on the mechanical performance, durability and aesthetics of the element. One of the most occurring defects is incorrectly located and misaligned fibre reinforcement. This can be caused by placement of the reinforcement in the wrong location, in the wrong order or due to resin flow induced wash away of the fibre reinforcement. Consequently, as the composite material cures the laminate can endure residual stresses, which reduces the performance and durability of the element, but can also show warpage and dissimilar or unwanted shrinkage. The latter features cause an undesired aesthetical effect[31].

The raw materials can cause defects or unexpected failure in two different ways. First of all it is possible that any of the materials used for the manufacturing of the element are not according to the specifications of the supplier, have surpassed their shelf-life or are contaminated with foreign substances. Secondly, and this is principally only applicable for the composite material, materials that are mixed together to form the composite laminate can react with each other. Additives responsible for this behaviour are fire retardants or pigments, or even contaminations, such as dust or absorbed moisture. The subsequent reactions between the materials can take place during the production process, or over longer periods when the element is subjected to weather influences. In all cases these material-related defects cause a lowered performance and durability of the element, and in some cases also accelerated or immediate aesthetical degradation[14] [31].

Besides the defects of which the origin is at the design, production process or materials, there is actually a fourth group of causes of defects, namely those that are unforeseen. Such damages are caused by, for example, accidental or intentional collisions during storage, transportation, installation or during service. Such failure causes will not be discussed in further detail.

14.2 Failure of the element during production

The number of defects that show during or immediately after the manufacturing of an FRP composite sandwich element are fairly limited. A failed production process can only be indicated by defects that become visibly through or on the outer layer of the element, or is confirmed when the element cannot be removed from its mould in one piece.

Damage of the element during extraction from the mould can have multiple causes. The most obvious cause is that the mould is insufficiently prepared, and pieces of the composite laminate or the gelcoat stick to the mould. Other possible causes for damage during the release process are related to the shape of the sides of the element and around the infill-blocks. Removal of the element from the mould can be difficult in case the draft angle is to steep, which is generally only applicable for infill-blocks due to shrinkage of the composite material. Another possibility is that the sides contain with the release procedure conflicting shapes. In this case the release process can require great effort and marks can be left on the surface. These kinds of defects find their origin in the design phase. Minor damage to the structural and finishing layer can be repaired, although such repairs tend to leave some marks. As the finishing layer is damaged it is important that the repairs are of sufficient quality, mainly to make sure that the structural layer behind the finishing layer is properly protected against weather influences when it is in service. In case larger pieces of the structural layer have broken off, or large cracks have appeared that go for a large part or completely through the entire structural layer, may pose notable risks and often do not allow for repair without the consequence that the entire element endures a significant loss of strength and stiffness[31].

Other prominent defects concern warpage or small distortions of the surface of the sandwich element, and also discolouration. As is discussed previously, warpage of the laminate generally occurs due to an incorrect placement of the fibre reinforcement prior to, or displacement of the fibre reinforcement during the impregnation with the matrix material. Other occurring distortions of the laminate can be hollowing, bulging or wave-forming of the flat surfaces. Such defects in the element occur when, during manufacturing, the material has too much room to move as the matrix is curing, or the mould has not enough stiffness and the impregnation of the fibrous material occurs under pressure or a vacuum. Such defects can principally not be repaired and the amount of materials and/or the mould need to be adjusted for further manufacturing. Discolouration of the surface mostly occurs when the application of heat is part of the production process, but is also possible when the raw materials are contaminated. Heat can influence the structural layer of FRP composite material and the finishing layer in two ways. Firstly, excessive heat causes these layers to deteriorate at an accelerated rate, which often shows itself by a slight change in colour. Secondly, heat can cause the occurrence of chemical reactions in the finishing layer and the matrix of the structural layer. Some additives in these layers can be stable in a normal service environment, but do react with each other, with the polymeric compounds or with contaminations at elevated temperatures. An example of such behaviour is known to occur between specific inorganic additives and organic polymers, and is called metal catalysed polymer oxidation. This reaction can occur in case an additive is based on a transition metal, such as copper, iron, cobalt, manganese or vanadium. Besides a change in colour it can be expected that the mechanical properties of the matrix are also negatively influenced in case such chemical reactions take place[14].

Delamination and blistering of the finishing layer, and entrapment of air and volatiles are defects that are somewhat harder to detect. Entrapment of air and volatiles creates voids in the composite layer and potentially between the composite layer and the finishing layer. The production of voids in the composite material generally occurs when the fibre impregnation is executed in a climate with a high relative humidity. Another cause is water vapour or other volatile gases that are released by the matrix during curing. High void contents are responsible for a decrease of the mechanical properties of the composite laminate. This is one of the main causes for blistering and delamination of the finishing layer in case a gelcoat is applied. Blistering and delamination of the finishing layer during or right after manufacturing can also be caused by an uneven surface of the substrate, presence of contamination on the substrate, or the application of an off-ratio mix for the finishing layer. Blistering of the finishing layer shows itself in the form of small bulges on the surface. Delamination of the finishing layer, in case it is occurred during manufacturing, is not necessarily visible to the naked eye. The surface could still be flat and similar looking compared to the remainder of the finishing layer, though there is a high probability that delaminated parts keep sticking to the mould and cause clearly visible defects on the element[14].

14.3 Failure of the element during service

Façades are designed for a specific service life, principally 25 or 50 years. During its service life it is required that the chance of failure of one of the façade element is very low. Possible failures during service is a complicated and comprehensive topic, but is only discussed briefly in this section.

Failure of the monolithic sandwich element during service shows itself in the begin stages as macro-cracking. These cracks are mostly caused by mechanical influences, such as fatigue or creep, or by exposure to weather influences due to peeling of the finishing layer. These damages increase the rate of deterioration of the entire element and continuation can lead to detachment of parts of the façade element. In the worst case the entire façade element will fall of the building. Macro-cracking normally starts at the areas in the laminate where stress concentrations occur, especially at the edges and corners of the laminate and connections where fasteners are applied. Degradation of the finishing layer during service is inflicted by a large amount of influences, and the rate of degradation is determined by a myriad of causes. On the one hand there are influences that cause chemical reactions. For example, sunlight and moisture may react with the finishing layer and possible the structural layer leading to UV degradation, heating and thermal oxidation, hydrolysis, and delamination and debonding. On the other hand, naturally present circumstances, such as sand, pollutants and water, can have an abrasive effect on the finishing layer[14] [48].

Experimental information that characterises the behaviour of the materials is required to design an element that can withstand both the service and ultimate conditions. However, since failure during the service period is often induced by natural influences, it is difficult to predict future service conditions. Considering the mechanical behaviour, both static and time-dependent, a margin is built in the calculations with the application of safety factors that are prescribed by the different available guidelines. As for the durability of the finishing layer, it must be taken into account that test results of accelerated weathering tests may deviate from the ageing and degradation process under real conditions[7] [14].

14.4 Damage assessment

The state a monolithic FRP composite sandwich element is in right after production can principally only be assessed on what is visible on the outside. In case the element is damaged and it is visible, the element should be repaired or discarded. Chances are that any defects in the element are not completely or not at all visible at the surface. Regarding this situation, the sandwich elements should still be capable of withstanding the required residual strength load level, and the structural integrity of the element may not be compromised since the element does function as a bearing structure.

Damages and flaws can be divided into two groups, namely visible and invisible. The easily notable damages are the ones that penetrate the finishing layer, such as abrasions, cracks, cuts, gauges, holes and scratches. As long as the laminate is not damaged, these impairments can be repaired without much effort. Cracks, cuts and holes have the tendency to enter or pass through the entire composite laminate, creating disruptions in the fibre reinforcement or reducing the integrity of the laminate. In this case it needs to be considered whether the location of the damage is critical or not, and subsequently if the element can be repaired or should be discarded. Other visible irregularities concern dents, warpage and rippling. These undesired deformations are less obvious, but important to discover before the element is assembled. Not only do deformities in the laminate indicate that there is something wrong structurally or with the integrity of the sandwich element, any deviations of the element with the design can complicate the assembly and installation process of the façade elements[48].

Several types of defects in the monolithic FRP composite sandwich elements are not visible on the outside of the element. This makes this group of defects quite dangerous. To this group belong delamination within the structural laminate or in the connection layers between the structural laminate and the core and finishing layer, high porosity and voids, inclusions of foreign particles, and local debonding and micro-cracking. Principally, all these flaws are caused by a faulty production process, but the challenge is the detection of the flaws and finding the cause within the production process. Since for façade elements aesthetics are paramount, only non-destructive testing (NDT) methods may be applied to search for potential damages. Most available NDT methods are only usable on a small scale, for example the tap test where the laminate is tapped on with a small hammer, or are not realistic to apply due to the size and build-up of the elements or the costs of the equipment. Ultrasonic testing methods, such as pulse-echo, through-transmission, back-scattering, acousto-ultrasonics and ultrasonic spectrocopy, are NDT methods that can be used for the inspection of large surface areas and large elements. Though, and this is also applicable for the other methods, ultrasonic testing methods are normally used for individual FRP composite laminates, not in case the laminates are applied in a sandwich structure. Very little information is available when it comes to inspecting FRP composite sandwich elements, but research indicates that it should be possible to apply one or more of these ultrasonic inspection methods for this kind of elements[48] [56] [57].

Chapter 15

Quality Control of the Materials

From the delivery of the raw materials for the production of monolithic FRP composite sandwich elements up to the moment the materials are used for production, there are two things that need to be assessed and are generally part of the quality control of the materials. First of all, storage of the materials needs to be regulated. Temperature, moisture and UV light have the potential to influence and even degrade the materials. Especially the polymer based materials are sensitive to these kinds of external influences. Furthermore, storage in locations with a high relative humidity or in dusty environments can cause accumulation of water or inclusion of foreign particles in the composite laminate as it is produced. Prior to production, the exact material properties of the reinforcement material, the polymeric compounds and additives need to be verified. However, this is very difficult, tedious to execute and requires specialised and expensive equipment [16] [48].

Considering the reinforcement, the fibrous material is expected not to change significantly from the moment of manufacturing until it is used in the production of the composite laminate. Also the manufacturer generally executes the necessary tests and can provide the technical data sheet containing the material properties. This makes additional testing before use principally superfluous. However, in case mats of stitched unidirectional fibre mats or woven fabric are used, one can see the state of the fibre reinforcement. As soon as mats with complex compositions are used, containing multiple layers of unidirectional fibres with different orientations and optionally flow mats on the outer sides, it is much more difficult to make a visual assessment of the fibre reinforcement in order to verify if it is in correspondence with the design. As is indicated by simple tensile tests with quadraxial fibre reinforcement, where the composition of the reinforcement does consist of multiple layers of fibres with different orientations, as soon as the fibre reinforcement deviates from the intended composition, so do the resulting properties of the composite laminate, causing a precarious situation. A method of investigating the correctness of the composition of the fibre reinforcement is cutting out a small sample with predefined dimensions and weighing the sample to verify if the reinforcement contains the correct amount of fibrous material. Subsequently the sample can be dissected in order to examine the build-up of the reinforcement. Although this analysis is not extremely accurate, this method allows potential flaws in the composition of the fibre reinforcement mats to be detected[48] [55].

Both the gelcoat and the resin for the composite laminate are another story. The properties, and therefore also the quality of polymeric compounds change in time. The degree of change is also influenced by the conditions in which these compounds are stored. Since the viscosity is one of the influencing factors of the VARTM production process, which is applied for manufacturing monolithic sandwich elements, it is advised to verify this property before processing. There are multiple test methods available, it is easiest to apply the same test method as the manufacturer has used, so that the test results can be compared. Actual verification of the polymeric compounds is significantly more difficult, and also the required equipment and execution of the test are much more expensive. There are several types of chromatography methods available with which these tests can be executed. It must also be noted that not only deviations in composition of the polymeric compounds are of influence on the performance of the end-result. These compounds need to be mixed with a catalyst and optionally other ingredients before the intended curing process starts. Furthermore, the influence of the conditions during curing on the end-product cannot be neglected[48].

Chapter 16

Quality Control of the Production Process

For both the production of the monolithic sandwich elements and the moulds it is applicable that a small mistake can ruin the entire product. Therefore, it is advised to follow an accurately compiled checklist for each step of the production process. Furthermore, and as is mentioned in the previous chapter, the properties and quality of the materials the end-product is composed of, are to a large extend dependent on the production process and the conditions under which the product process is executed.

Verification of the various dimensions and amounts of all equipment, components and materials involved is relatively easy. Monitoring the composition of the mixtures used, and the external influences during the production process take slightly more effort and the effects of these subjects are easily underestimated. After the necessary preparations, the actual production of the elements starts out with mixing the polymeric compounds with the catalysts and additives, first the gelcoat, and after applying the fibre reinforcement and core, the matrix. Although this has the appearance of an easy job, any errors in the execution can have extensive consequences. Regardless if this process is carried out manually or automatically, it requires the precision and careful execution to prevent off-ratio mixes, contaminated, and poorly mixed and thus inhomogeneous compounds. The compounds are applied directly after mixing. In case of the application of VARTM, the gelcoat is applied manually in an open environment, the matrix is inserted automatically in a closed-off environment. Monitoring and controlling the applied amounts lead to obtaining the desired thickness of each layer. As for the application of the fibre reinforcement and to a lesser extend the core material, it is important that these components are not only in the correct amount, but also in the correct order and with the intended orientation. When the matrix has cured, the monolithic sandwich element can be removed from the mould and is the sandwich element principally finished. This is the moment that the appearance of the product needs to be checked for damages and flaws, followed by the approval or rejection of the element. Part of this inspection consists of the verification of the exact shape and size of the end-product prior to assembly to assure a perfect fit of the remaining components and installation of the façade element in the field[16] [31] [48].

The points of attention described above are all important due to presence of manual labour in the production process. The second influencing factor mentioned is the influence of the external conditions during the process. This concerns the interior environment in the facility where the production process takes place, but also the artificially created conditions the sandwich element has to endure during the curing and post-curing stage. Since this is of influence on the appearance and performance of the end-product, it can be assumed that any variations in these conditions between the production of multiple sandwich elements lead to variations in appearance and performance between the sandwich elements. It is therefore advised that both the conditions in the production facility and the cure and post-cure process are kept consistent during the manufacturing of all elements that are part of a single project[14] [16] [31] [48].

Since the materials, in the form they are supplied, are difficult to test, and the performance is largely dependent on the mixture of the polymeric compounds and the execution of and conditions during the production process, the performance of the FRP composite laminate applied in the sandwich element can be approximated by making a test laminate alongside the actual element. From the test laminate test specimens can be cut and tested. Assuming the laminate has the same composition as the laminate in the sandwich element, the results can be used as a verification of the quality of the end-product. Furthermore, in case a façade element fails during service, test specimens coming from the corresponding test plate can be tested to ascertain the material properties of the laminate and narrow down the mode and cause of failure. Additionally, it is important that during production a proper administration is kept of all the used materials, so that the failure of a single element during service can be related to a particular batch of elements that might be affected[14] [48].

Part IV

Research Evaluation

Chapter 17

Discussion

The concept of basing unitised façade systems on monolithic FRP composite sandwich elements has the potential to become the standard façade system, assuming that the concept becomes more affordable and the grip on quality and durability of the materials increases. With the ability to take virtually any shape and size, and the higher thermal resistance compared to the older systems, this concept is not only usable for new buildings, but is also highly suitable for the renovation of existing buildings.

The consequence of the flexibility of this concept and the materials, and thereby also a major downside, is the accompanying complexity. The system analysis shows that numerous amounts of factors are involved in the design and production process, and that all the factors also have an influence on each other to a greater or lesser extent. Though a lot of interesting new technologies have been and are being researched concerning FRP composites, by far the biggest part of these studies are applicable on high-performance composites. Only a small part of the studies have been executed with or are assumed to be also applicable on engineering composites, similar to what is used in the building industry. The same applies for recent studies that are set up to develop a method of predicting the strength and stiffness of composites. There is, however, another issue with these recent studies. Often in such studies it is tried to predict or approach the material properties of a very specific composite build-up with a finite element method or other computer modelling analyses. This kind of research setup restricts both its application and usability for different material compositions.

It is striking that only a couple of the factors take in a critical position in the concept of FRP composite sandwich elements. These key factors, the matrix, the fire behaviour of the element, the execution of the production process and the connections with the critical components, all dominate the design and production processes. Choices made concerning these factors have a major influence on the durability of the entire element, the difficulty in design and production, the chance of flaws and failure during manufacturing and on all the other aspects of the concept. This makes it very challenging to make the right decisions in order to come to a balanced design. Both design and manufacturing methodologies, and production guidelines that account for FRP composite materials, recommend simplicity and consistency in both processes, as opposed to complex detailing and the application of deviations between the elements. This is especially true for these four factors and possible solutions for issues regarding one or more of these factors.

That, which in this research is investigated, offers sufficient food for thought on the current state of the concept. Furthermore, the most influencing aspects of the concept are pointed out, together with potential issues that can arise during further development of the concept. Overall a useful basis is presented, but further and more focused research is required to solve current issues and make optimisations to the concept, all in order to make future applications of this concept more profitable.

Chapter 18

Conclusions

The application of monolithic FRP composite sandwich elements as bearing structure and closed sections in unitised façade systems is accompanied with a lot of potential. However, a substantial amount of pitfalls and unknowns arise due to the novelty of this concept in the building industry. With the stated research question in the introduction, an inquiry into the current state and analysis of the concept, including the research for potential improvements in the associated design and production process, is summarised in a single sentence:

"Is it possible to ameliorate the design and production process of current systems consisting monolithic FRP composite sandwich elements with currently available knowledge, technology, and materials, thereby improving the ease and flexibility in design, and improving the quality and reducing the costs of the finished product?"

In the system analysis the different aspects of the concept are examined, thereby analysing the state-of-the-art and reviewing the available improvements and alternatives. Though a lot of factors and influence pass during the analysis, a few "key factors"take in a critical position in the entire process:

- Matrix: The polymeric compound that is part of the FRP composite material in the structural layer of the sandwich element and the part of the sandwich element that is responsible for the integrity of the entire element.
- Fire behaviour of the element: Principally the cheapest for FRP composites applicable resins are based on polyesters, and polymeric compounds based on polyesters are inherently flammable.
- Production process: Not only is the production process of influence on the quality of the end-product, the exact execution of and circumstances during manufacturing elements with this production process have also a major impact.

- Critical components: FRP composites require a different mindset when it comes to connections and the transfer of stresses compared to traditional building materials, such as steel and aluminium.

These four key factors have one thing in common, namely that design choices and actions during production made, regarding these factors, are assumed to have a significant influence on the durability of the end-product. Though, due to the fact that this concerns unfamiliar territory, the actual consequences cannot be quantified. Reviewing currently available materials and technologies, the potential issues that accompany these factors are not insurmountable, but ready-made solutions are not yet available. Each of the issues requires further research and live testing. Consequently, solving these issues regarding these key factors may not only increase the quality and durability of the end-product, but might also increase the ease in design and the overall costs.

The unfamiliar territory continuous with designing the structural laminate of the sandwich elements. For the structural design numerous engineering constants are required to be known, which are currently by default determined with help of physical testing for every new composition of FRP composite material. These tests are expensive in both money and time, and replacement of the tests with an analytical calculation method would save both.

Existing calculation methods that initially qualify are the Rule of mixtures, the Halpin-Tsai method and the Chamis equation. Interestingly, resulting from a comparison of these methods with real-life test results, these methods seem usable for predicting multiple engineering constants. Although, this is limited to the ones that describe the stiffness of FRP composite laminae in its plane. As a result of the comparisons made it can be concluded that the method that displayed generally the highest accuracy is the Halpin-Tsai method. Furthermore, the analysed methods show that the means for determination of the strengths of FRP composite laminae are far less developed compared to what is available for ascertaining the various moduli. Nevertheless, even the resulting moduli that are determined with the currently available methods should only be treated as indicative values and not characteristic material properties, especially considering the significant amount of scatter in some of the test results. All things considered, with the current state of predicting the material properties analytically, the designed FRP composite laminate is still required to be subjected to the various tests.

The quality and durability of the elements, and the extent of the accompanying quality assessment, are dependent on the design, the applied materials and the execution of the production process. Any defects in the end-product, both visible and invisible, have the same origin. Consequently, potential defects have an impact on the mechanical performance, durability and/or aesthetics of the element.

Errors caused by the design are generally discovered during the production of a first set of test elements, or during the tests these element are subjected to. These errors can often be prevented by running simulations. Elements that are flawed due to the applied materials or the production process show their defects right after production, or in the worst case scenario when the element is in service. A complete and thorough visual inspection of the produced composite sandwich element is required, but only the defects that show themselves as irregularities on the surface can be found with this kind of inspection. Internal defects, such as delamination, high porosity and voids, inclusions of foreign particles, and local debonding and micro-cracking are often not visible on the surface due to the presence of the finishing layer. These types of defects are generally small, but might have a significant influence on the durability of the element. These flaws can only be discovered with extensive non-destructive testing (NDT) methods, of which ultrasonic testing methods are the most feasible for sandwich elements.

It is more important to prevent errors by enforcing a strict quality control program. For the production process this concerns following an extensive checklist that covers the execution steps and conditions. Regarding testing the materials it can be concluded that verification of the quality is very difficult. The required tests are often expensive, time-consuming and tedious to execute. Since the end-result is dependent on both the materials and the execution of the production process, it is more useful to test specimens that are cut from a test laminate, which is produced alongside the actual element with the same composition. By testing these specimens the actual performance and quality of the FRP composite laminate that is applied in the sandwich element can be verified. The specimens can also be tested as a control in case the corresponding element fails during service.

Overall it can be concluded that it is possible to improve the concept, and also the design and production process that accompany the concept, but with some constraints. For each issue that has arisen during each of the analyses, one or more potential solutions are available with currently available knowledge, technology, and materials. However, and this is one of the lessons learned from the system analysis, every change made on the state-of-the-art can have unexpected influences on several other factors. Solving current issues and standardising parts of the design and production processes will most likely take some iterations before a profitable working concept is developed.

Chapter 19

Recommendations

Firstly, the flammability of the materials, that together form the FRP composite sandwich element, is the most pressing issue, noting that this requirement shows a major interdependent relation with the matrix. The fire resistance and maximum smoke production are set by always applicable requirements, independent of the shape and design of the elements. The solution for this issue should therefore also be independent of the shape and design. There are actually two options available, which have already been discussed previously, namely changing the composition of the matrix or adding an additional layer between the finishing and structural layer. As for the matrix, currently the issues regarding fire behaviour are solved by adding micro-fillers, which increase the fire resistance of the matrix, but are expected to have a negative influence on the cohesive and adhesive properties of the matrix. Initial research has shown that replacing this additive with nano-fillers can show similar results with respect to the fire behaviour, without reducing the integrity. The second option concerns adding a layer that shields the structural layer from excessive heat by forming a thermal barrier or intumescence. Tests have shown that both options are feasible, but further research and tests will have to show which of the two options functions best, is cheaper, is easier to apply and has the lowest chance of failure during production.

Additionally, meeting the requirements concerning fire resistance and smoke production is not the only thing that should be considered here. Often the materials used for solving problems with fire behaviour cause the release of toxic gases in case these materials are heated. And although it is currently not a generally applicable demand or required by law, it is advised that the solution that will be applied in these sandwich elements does not introduce new problems concerning toxicity.

A second recommendation that follows this research concerns the connections between the several components of a façade element with the monolithic sandwich element. Mounting the sandwich element, and thereby the entire façade element to the bearing structure of the building is the single most important connection of the entire system. However, with the application of a new material, the FRP composite laminate, a new method of designing connections should be introduced. An FRP composite laminate is the strongest and least sensitive to premature failure if it is completely uninterrupted. Therefore, in order to increase the durability of the element, the necessity of connections with screws or bolts needs to be eliminated. There are multiple options available that have the potential to replace current systems. The easiest one is to glue a metal component on the sandwich element that hooks into the mounting system on the bearing structure. More complex solutions include integrating a metal or composite component in the sandwich element, or creating a specially formed cavity in the sandwich element in which the mounting system grabs the façade element. Consequently, standardisation of the mounting system will increase the ease in design and reduce the overall costs.

The last recommendation concerns an aspect of designing and producing with FRP composite materials. As is shown in the material analysis it is very difficult to predict all aspects of this type of material, and development of an all-encompassing calculation method, especially the part regarding the determination of the strength in the various directions, has yet a long way to go. The development of this method is extremely comprehensive and will take a large amount of time and resources. This task is therefore likely to be divided into multiple studies, which optimally are coordinated and supervised by a single institution or umbrella organisation. It is important that continued research starts with the most basic laminae and build on from there.

Glossary

Research and documentation concerning FRP composite material are rather spread-out and often applicable for very specific purposes and industries. Overall it is common that a specific term has multiple definitions or that a connotation is assigned multiple terms. In order to avoid any further confusion, a number of the definitions as described in this glossary is copied partially or as a whole from the glossaries of leading documentation[7] [29].

Accelerator — Also known as promoter, is a material that when added to a catalysed resin, speeds up the polymerisation process of the resin.
Additive — Any substance added to another substance, added to improve specific properties, such as mechanical properties or fire behaviour.
Adhesion — The state in which two surfaces are held together at an interface with a chemical or mechanical bond, or a combination of the two.
Adhesive — A material used to join or bond materials.
Ageing — The effect(s) resulting of exposure to an environment on a material for an interval of time.
Anisotropic — Exhibiting different properties when tested along axes in different directions.
Aramid — A type of highly oriented organic material derived from polyamide, or nylon, but incorporating an aromatic ring structure.
Aramid fibre — Fibrous material made from aramid.
Aspect ratio — The ratio of length (and/or width) to diameter of thickness.
Autoclave — A closed container for conducting an operation under pressure and heat.

Bidirectional lamina(te) (*biaxial (BIAX) fibre reinforced*) — A reinforced plastic lamina or laminate with continuous fibres oriented in two directions, generally oriented $\langle 0°, 90° \rangle$ or $\langle -45°, 45° \rangle$.

Capillary effect — The movement of a liquid substance along the surface of a solid material caused by the attraction of molecules of the liquid to the molecules

of the solid.
Carbon (*graphite*) — A non-metallic element that provides the backbone for all organic polymers. Graphite is a more ordered form of carbon.
Carbon fibre — Fibrous material produced from a precursor polymer, such as polyacrylonitrile (PAN) carbon, rayon, or mesophane pitch carbon, with an elemental carbon content of $\geq 95\%$.
Catalyst — A substance that initiates a chemical reaction, without being involved in or changed by the reaction.
Char-forming — The formation of insulative foamed carbonaceous chars in case the material is exposed to fire.
Closed-cell foam — A substance formed by discrete pockets of entrapped gas (air), in which each pocket is completely surrounded by the solid material.
Coefficient of thermal expansion (CTE); α $[K^{-1}]$ — The change in length per unit resulting from a 1-degree rise in temperature.
Coefficient of thermal conductivity; λ $[W/(mK)]$ — The property of a material to conduct heat.
Cohesion — The force of attraction that holds molecules of a single given substance together.
Composite — A complex material in which two or more distinct, structurally complementary substances are combined to produce structural or functional properties not present in any individual component.
Compressive modulus of elasticity (*bulk modulus*); K $[N/mm^2]$ — Ratio of compressive stress to compressive strain below the proportional limit.
Conductivity — A measure of the thermal or electrical conductance of a substance. Conductivity is the reciprocal of resistivity.
Co-polymer — A polymer consisting of two or more different monomers.
Corrosion — Deterioration of a material by chemical, electrochemical or electrolytic reaction with its environment.
Creep — The change in dimension of a material under sustained load over a period of time, not including the initial instantaneous deformation. A normal occurrence in visco-elastic materials.
Cross-linking agent — A substance (monomer) that mixed with a polymer substance reacts with the polymer substance under certain circumstances, creating covalent or ionic bonds (cross-links) between two polymer chains. This reaction is part of the curing process of thermosetting resins.
Cure — To irreversibly change the properties of a thermosetting resin by chemical reaction, turning the liquid resin into a solid or gel. Cure is accomplished by addition of cross-linking agents, with or without the application of heat and pressure.

Deflection — Movement of a point on a structure that is measured as linear displacement transverse to a reference line or plane.
Delamination — A separation of layers along a plane parallel to a surface.
Diluent — A substance used to dilute.
Dimensional stability – The ability of a system to maintain its original or de-

sired dimensions during service.
Durability — The ability of a system to maintain its properties with time and the ability to resist the influences of the conditions of service.

Fastener — A device meant for fastening, e.g. a bolt or screw.
Fatigue — The failure of decay of mechanical properties after repeated or alternating applications of loading.
Fibre orientation — The angle under which unidirectional fibre is placed relative to 1-axis of the assumed principal material coordinate system.
Fibre reinforced polymer (FRP) — A general term covering any type of polymer reinforced fibrous material.
Filler — A material added to a compound in order to reduce cost, or intentionally modify its material properties.
Fire barrier — A layer surrounding a structure with a high fire resistance that protects the substrate from the influence of direct contact with fire.
Fire behaviour — The behaviour a material shows when it is exposed to fire. This concerns the flammability of the material in combination with the accompanying smoke production.
Flame retardant (*fire retardant*) — A material that is used, often as additive, to reduce the tendency of a system to burn.
Flammability — Measure of the extent to which a material will support combustion.
Flexural rigidity; D_κ $[Nmm^2]$ — An engineering constant composed of the product of the tensile modulus (E) and the moment of inertia (I) of a system that describes the capability of offering resistance while undergoing flexural deformation.

Gel-time — The interval of time in connection with the use of synthetic thermosetting resins, extending from the introduction of a catalyst into a polymer compound until the moment of gel formation.
Gelcoat — A coloured polymer compound used as a surface coat for moulded FRP composite elements. It provides a cosmetic enhancement and environmental protection for the FRP composite laminate underneath.
Glass fibre — Fibre drawn from an inorganic product of fusion in the form of a filament that has cooled without crystallising.
Glass transition temperature; T_g $[°C]$ — The midpoint of the temperature range over which an amorphous material changes from a brittle, vitreous state to a plastic state, or vice versa.
Graft co-polymerisation — The replacement of co-polymers in a polymeric compound with specific monomers to improve specific material properties of the polymer.
Graphite fibre — Fibrous material comparable to carbon fibre. Its manufacturing process is more extensive and requires higher temperatures giving the material a more ordered structure and higher content of elemental carbon ($\geq 99\%$).

Halogenated resin — A resin containing chlorine or bromine based additives in order to reduce its flammability, but has the tendency to release toxic gases as it is subjected to fire.
Heat deflection temperature; HDT $[°C]$ — The temperature at which a plastic material has an arbitrary deflection when subjected to an arbitrary load and conditions, and is an alternative for the glass transition temperature.

Impregnation — Saturation of voids and interstices of a reinforcement material with a matrix.
Inhibitor — A substance which retards a chemical reaction.
Initiator — A substance that starts a chain reaction, which can both participate in the reaction or serve as catalyst.
Interface — The boundary or surface between two different, physically distinguished media.
Interphase — The connection layer between the fibrous material and the matrix in a composite laminate.
Intumescence — The swelling of certain substances in case it is subjected to excessive heating.

Lacquer coating — A polymeric resin based coating that is applied of prepared surfaces, and is an alternative for a gelcoat.
Lamina — A single layer, in context with FRP composites a layer that can consist of one or more plies placed directly on top of each other, where each of the plies has the same fibre reinforcement with the same orientation.
Laminate — A plate element composed of one or more laminae.

Macro-cracks (macro-fractures) — Cracks, often visible to the naked eye, formed in a system when stresses exceed the strength of the matrix and potentially also the reinforcement.
Matrix — A substance within which another material, often a form of reinforcement, is contained, thereby functioning as a binding component providing structural integrity to the resulting system.
Micro-cracks (micro-fractures) — Cracks formed in a system when stresses locally exceed the strength of the matrix.
Micro particle filler — A filler material of which the dimensions of the particles are smaller than 100 μm.
Modulus of elasticity; E, G, K $[N/mm^2]$ — The ratio of the stress or load applied to the strain or deformation produced in a material that is elastically deformed. Here discussed moduli are tensile modulus (E), shear modulus (G) and bulk modulus (K).
Monomer — A simple molecule which is capable of reacting with similar or dissimilar molecules to form a polymer, e.g. the smallest repeating structure of a polymer.

Nano particle filler — A filler material of which the dimensions of the particles are smaller than 100 nm.
Nanoclay — A natural occurring mineral (montmorillonite), which can be assigned to the group of nano particle fillers.

Open-cell foam — A substance formed by pockets of entrapped gas (air), in which the pocket are not completely surrounded by the solid material and are connected to each other.
Orthotropic — Having three mutually perpendicular planes of elastic symmetry, each usually with differing properties, as is typical for FRP composite laminates and wood.

Peeling — A process in which layers detach from each other due to adhesive or cohesive failure of the bond, often induced by excessive local tensile stresses or weather influences.
Ply — A single layer, in context with FRP composites a lamina or laminate that contains a single layer of fibre reinforcement.
Poisson's ratio; ν $[-]$ — Ratio of the change in width per unit width to the change in length per unit length.
Polymer - A high molecular weight organic compound, natural or synthetic, whose structure can be represented by a repeated small unit. Occurring types of polymers are elastomer, thermoplastic and thermosetting.
Porosity — The ratio of the volume of all air or void content in a material to the volume of the whole.

Quad-directional lamina(te) (quadraxial (QX) fibre reinforced) — A reinforced plastic lamina or laminate with continuous fibres oriented in four directions, generally oriented $\langle -45°, 0°, 45°, 90° \rangle$, with generally 25 % of the total fibre content in each direction.
Quality assurance — A system of proceedings that ensures that the intended levels of quality on a project or product are obtained.
Quality control — A system of tests and inspections that ensures the maintenance of proper standards in used materials and manufactured goods.

Reactive diluent — A substance that serves as both a diluent and as a cross-linking agent.

Saturation — The state of a physical system in stable equilibrium, such as a solution, containing as much of another substance, such as a solute, as is possible at a given temperature or pressure.
Sizing — A treatment consisting of starch, gelatin, oil, wax or other suitable ingredient, which is applied to fibres at the time of formation to protect the surface and aid the process of handling and fabrication.

Shear rigidity; D_γ $[Nmm^2]$ — An engineering constant composed of the product of the shear modulus (G), the cross-sectional area (A_{cs}) and a shear coefficient (k) of a system that describes the capability of offering resistance while undergoing shear deformation.

Smoke retardant — A material that is used, often as additive, to reduce the smoke release of the system as it is exposed to fire.

Static behaviour — The behaviour a system displays as it is subjected to static loading.

Stress relaxation — Stress relaxation is the occurrence of a decrease of stresses in the structure, while the deformation is held constant. This causes permanently deformed shapes of the structure after mechanical and thermal loads are removed.

Thermal barrier — A layer as part of a system that protects the substrate from the heat source the system is subjected to.

Thermal behaviour — The behaviour a system displays as it is subjected to varying temperatures.

Thermal resistance; R_c $[m^2K/W]$ — A material property describing a measurement by which an object or material resists a heat flow at a specified temperature difference.

Thermoplastic resin — A polymer based compound that is capable of being repeatedly softened by increase of temperature and hardened by decrease in temperature.

Thermosetting resin — A polymer based compound, which, when cured by application of heat or chemical means, changes into a substantially infusible and insoluble material.

Time-dependent behaviour — The behaviour a system displays as it is subjected to long-term influences, such long-term static or dynamic loading, or weathering.

Ultimate compressive strength; $f_{u,d}$ $[N/mm^2]$ — The maximum capacity of a material or structure to withstand compressive stress.

Ultimate shear strength; $f_{u,V}$ $[N/mm^2]$ — The maximum capacity of a material or structure to withstand shear stress.

Ultimate tensile strength; $f_{u,t}$ $[N/mm^2]$ — The maximum capacity of a material or structure to withstand tensile stress.

Unidirectional lamina(te) (unidirectional (UD) fibre reinforced) — An FRP composite laminate in which principally all fibres are oriented in the same direction.

Unitised façade system — A façade system consisting of prefabricated façade elements that are installed on site.

Viscosity; μ $[Pa \cdot s]$ — The internal friction resistance of a liquid to flow when that resistance is directly proportional to the applied force.

Volatiles — Materials in a system that are capable of being driven off as a vapour at room or slightly elevated temperatures.

Weathering — Changes in any of the material properties due to exposure of climatic conditions, e.g. moisture, temperatures and UV radiation.

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Next Generation Façades

In this master thesis, which is executed as part of the master program Building Engineering at Delft University of Technology, the world of fibre reinforced polymer composites is explored as this material is applied in monolithic sandwich elements that function as bearing structure in unitised façade systems. This novel application in the building industry is accompanied with a lot of potential, but due its novelty the development of the concept is afflicted by a large amount of problems and unknowns. The research presented in this thesis aims at providing an answer to the question if it is possible to ameliorate the design and production process of the current state of the concept with currently available knowledge, technology, and materials. Furthermore, it is investigated if the ease and flexibility in design could be improved, the quality of the finished product could be enhanced and the costs could be reduced.

The research is divided into three main parts. The first part of this research covers a complete system analysis of the concept, discussing aspects and interdependent influences of applicable materials for the sandwich element, production processes, critical components of façade elements, technical specifications, shape and design, and environmental influences. With the system analysis an attempt is made to create some order in the complex system that surrounds the concept. The second part of this research focuses on improving the design process of the monolithic fibre reinforced polymer composite sandwich elements. This part comprises an analysis on the accuracy and applicability of existing calculation methods as they are compared to test results, and an investigation into the behaviour of the material. The third part builds on this by examining the methods of failure of the composite material, and the accompanying quality control for both the materials and the production process.

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