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OPTIMISATION OF CARBON COMPOSITE CONSTRUCTION WITH COMPUTATIONAL TECHNIQUES

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A meus Pais e irmão

Perfection is achieved, not when there is nothing more to add, but when there is nothing left to take away.

Antoine de Saint-Exupéry

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ABSTRACT

Structural optimisation techniques have evolved throughout the years in great part due to the increase of computational power available in engineering practices. This evolution has given access to fast, accurate and cheap analysis that enabled engineers to design structures with increasing confidence [1]. However, these new methodologies also bring new challenges. Although technology has evolved, it is increasingly hard for the general engineer to understand what methods the software is adopting culminating in a "black box" mentality. For this reason, it is important to be familiarized with the theoretical background of the chosen tool.

As software evolves to become more versatile, new opportunities to experiment with different geometries and materials emerge.

Applications of fibre composite materials have been explored in aerospace, nautical and automotive industries with great performance resulting in reduced weight and optimised aerodynamics. These materials are characterised by having a high strength-to-weight ratio and can be manipulated to generate complex geometries. Although such characteristics create a great potential for applications in architecture and structural engineering, they have remained unexplored in recent years.

This thesis was developed in partnership with Format Engineers and aims to study the optimisation of carbon fibre composite structures using computational tools.

The study has focused on topology optimisation and the selection of the most adequate computational tool for the design of a carbon fibre structure. For this study, the chosen structure was a carbon fibre canopy.

The design of the carbon fibre canopy started with the setting up of an optimisation problem and the selection of carbon fibre rovings as the canopy's load bearing structure material, followed by a study of the geometry based on a layout optimisation tool – Peregrine [2] (an optimisation plugin for Grasshopper [3]). From the array of options, a comparative analysis was carried out in order to select the final form of the canopy which was then subjected to a structural analysis using Karamba3D [4].

Lastly, a study of the construction process was done in order to complete all the design aspects of this project. To help with this, a scaled model of the structure was developed.

The final results include the final geometry for the structure, detailing of the connections and respective map of quantities, and the proposal for the fabrication process.

KEYWORDS: Optimisation, Topology Optimisation, carbon fibre composites, CFRP, Canopy

RESUMO

Ao longo do tempo, as técnicas de optimização na engenharia de estruturas têm sofrido desenvolvimentos e avanços em diferentes aplicações. Grande parte desta expanção é devida ao aumento do poder de computação disponível também na indústria da construção. Atualmente, são utilizados, na prática corrente da engenharia, softwares capazes de realizar, rapidamente, análises estruturais com elevada precisão. Consequentemente, a introdução destas ferramentas exige o desenvolvimento de novas metodologias de trabalho por parte dos engenheiros. Estas acabam por incentivar a procura de um maior nível de conhecimento para utilizar estes softwares e, por isso, uma maior consciência dos métodos por eles adotados. Desta forma, previne-se a mentalidade de "caixa negra" perante o funcionamento de softwares que pode, em última instância, ter consequências desastrosas.

À medida que os softwares se tornam mais versáteis, surgem oportunidades para experimentar e testar novas geometrias e materiais com propriedades distintas.

A aplicação de materiais compósitos de fibra de carbono foi essencialmente explorada nas indústrias aeronáutica, aeroespacial e automóvel. Indústrias estas que obtiveram grandes ganhos em eficiência com redução de peso e otimização da aerodinâmica já que permite uma grande liberdade de geometria. Apesar do potencial das suas características, a aplicação de materiais compósitos de fibra de carbono na conceção de estruturas tem sido muito escasso em anos recentes, salvo algumas exceções que por norma pertencem ao domínio académico.

O presente trabalho foi desenvolvido com a colaboração da Format Engineers, e procura estudar a aplicação de métodos de otimização em estruturas de compósitos de fibra de carbono recorrendo a técnicas computacionais.

O estudo focou-se na otimização da topologia e na seleção da ferramenta mais adequada para a conceção e análise de uma estrutura em fibra de carbono. Com este intuito, adotou-se como caso de estudo a conceção de uma cobertura em compósitos de fibra de carbono.

Começou-se por definir o problema de optimização e a escolha de rovings de CFRP como o material principal da estrutura. Após estabelecer estes detalhes, passou-se para um estudo da geometria baseada na ferramenta que executa uma optimização de layout – Peregrine [2] um plugin de otimização para o software Grasshopper. Deste estudo obtiveram-se várias soluções que foram analisadas recorrendo ao plugin Karamba3D. Este assegurou uma análise estrutural de cada geometria de acordo com os respectivos casos de carga e as propriedades do material, de forma a escolher a melhor solução.

Por fim, efetua-se um estudo breve dos métodos construtivos adequados à estrutura. Para auxiliar este estudo, desenvolveu-se uma maquete que pretende simular o método proposto para fabricação da cobertura.

O resultado final desta pesquisa é a definição da geometria para a cobertura, bem como o respetivo detalhe das ligações (quer as relativas às condições de apoio, quer às da ligação com o painel da cobertura) com o respectivo mapa de quantidades, e uma proposta do método de fabrico.

PALAVRAS-CHAVE: Otimização, Otimização Topológica, CFRP, Fibra de Carbono, Cobertura

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INTRODUCTION

1.1. OVERVIEW

Advances in technology and increase in computational power made possible the widespread adoption of powerful numerical methods to carry out structural analysis and optimisation [1].

Nowadays, there is a wide range of software packages available to engineers either for structural analysis, design, or optimisation. These tools offer architects and engineers the opportunity to explore new and creative solutions that were not available before. Also, through the use of these tools, it is possible to have a greater impact on creating more sustainable and economical structures. However, it is important to mention that it is the responsibility of the engineer to understand the processes behind the software and interpret the results accordingly.

Optimisation tools can be implemented right from the beginning at the conception phase and geometry studies, through form-finding or topology approaches. They can also be applied in the design stage of the process.

One important feature in most of these types of software is the possibility to work and experiment with different materials through the input of their mechanical properties (elasticity modulus, tensile strength, etc). In this way, it is possible to model each solution and obtain an accurate estimation of the expected behaviour of the real structure. Similarly, it is essential to understand the characteristics of the material to select the right approach and tools.

1.2. OBJECTIVES

This dissertation aims at the development of an adequate workflow for the implementation of optimisation techniques in the design of structures made of carbon fibre reinforced polymers (CFRP).

To develop a good workflow, some aspects need to be studied. Firstly, an adequate selection of the optimisation technique should be made, allowing for an accurate depiction of the problem at hands. Secondly, it is important to have a clear understanding of the material properties of, along with its advantages and disadvantages. In this way, it will be possible to adapt the problem to fit the material description and take advantage of CFRP. Finally, the selection of a computational tool that can fit both the selected optimisation technique and the material properties of CFRP.

The workflow is being developed and applied to a case study – the design of a carbon fibre canopy. The final result consists of a solution for the geometry of the structure, including the structural detailing along with a proposed fabrication process.

1.3. METHODOLOGY AND STRUCTURE

This research is grouped into three main parts, after this initial introduction. The first one, found in Chapter 2, consists of a review of the literature regarding the evolution of structural optimisation processes and the properties of carbon fibre reinforced polymers and its use in the construction industry. This first section culminates in the selection of an optimisation technique (which is then explored in more detail), and a discussion about the advantages and disadvantages associated to CFRP.

The second part, Chapter 3, describes the implementation of the workflow developed in the design and analysis of a carbon fibre canopy. It includes the geometry study and corresponding analysis of the results and the structural analysis for the final solution.

Lastly, the third part which includes Chapters 4 and 5 focus on the fabrication processes and the final results, respectively. Chapter 4 focuses on the selection of the adequate fabrication process to be used for the construction of the canopy. In Chapter 5, an overall review of the results is made.

1.4. REFERENCE PROJECTS

The work developed on this dissertation was based on a series of projects developed at the University of Stuttgart (the ITKE/ICD Research Pavilions). A series of pavilions made with carbon fibre and glass fibre combined with computational design techniques. These studies explore the application of a fabrication technique – coreless filament winding – in the construction of structures made of composite materials (namely carbon fibre reinforced polymers and glass fibre reinforced polymers). Two examples of these structures are shown in Figure 1 – ITKE/ICD Research Pavilion 2016-17, a single long spanning cantilever [5] - and in Figure 2 – ITKE/ICD Research Pavilion 2013-14, a modular system based on the internal structures in beetle shells [6].

Figure 1: ICD/ITKE Research Pavilion 2016-17, Stuttgart [5]

Figure 2: ICD/ITKE Research Pavilion 2013-14, Stuttgart [6]

2

STATE OF THE ART: STRUCTURAL OPTIMISATION AND DESIGN OF CFRP STRUCTURES

2.1. OPTIMISATION

2.1.1. BACKGROUND

The concept of optimisation has been ever-present in structural design. It is defined «loosely as the selection of the "best" design within the available means. » [7]. To be able to assess whether a solution is the "best" or not there needs to be a framing for the optimisation problem. In other words, the objective function, the problem constrains, and the "available means" must be known.

In structural design, the best solution is, usually, one which achieves good structural performance whilst minimizing the use of material, thus creating an efficient and more economical structure. In order to maximize the efficiency while also being economical in material usage, the shape of the structure should reflect the flow of forces created by self-weight and the applied forces in the structure [8]. In fact, this will lead to the reduction of bending and shear forces – the structure will work primarily in tension and compression [9] - allowing for an optimum use of materials. In extreme cases, bending and shear are completely eliminated, and the shape of the structure follows the load path. That is, the shape of the structure is a direct product of the loads applied – this process is known as *form-finding*. «*Form finding* is a forward process in which parameters are explicitly/directly controlled to find an 'optimal' geometry of a structure which is in static equilibrium with a design loading. » [8]

However, these geometries are not easily described through mathematics. Before the introduction of computers, engineers had to rely on scaled physical models in order to find these optimal geometries.

Throughout the 20th century, there are many examples of architects and engineer who explored novel methods of creating optimal forms of structures

Frei Otto applied form finding leveraging the properties of soap film in his scaled models [10]. In his studies, he used soap film to produce very thin membranes by dipping wire loops into soap. Such experiments are shown in Figure 3. With this method he was able to create lightweight membrane structures with uniform stresses in every direction – tensile stress. These surfaces are called minimal surfaces as they enclose the smallest possible area within a closed space curve. When applied to buildings they are used to design tensile membranes (with no bending stiffness) [10]. One of the many projects that illustrate Otto’s work was the Deutscher Pavillon, built for the 1967 World Exposition in Montreal, Canada (Figure 4).

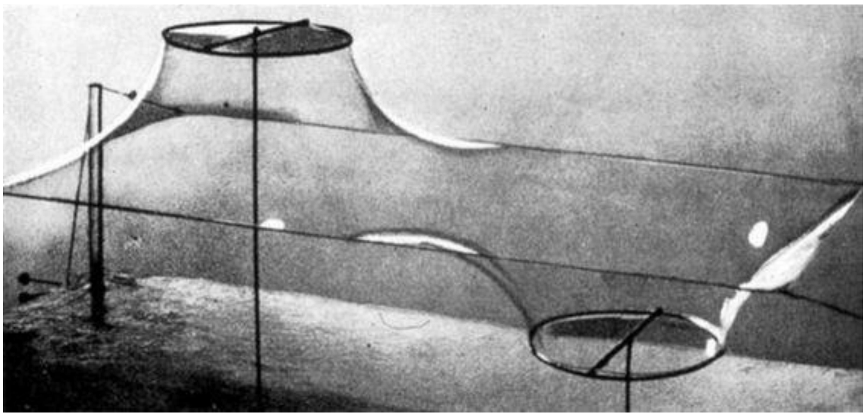


Figure 3: Frei Otto's soap film experiments

Figure 4: Deutscher Pavillon at Expo’67 in Montreal, 1967, Frei Otto and Rolft Gutbrod

Another good example of optimum forms are Antoni Gaudí’s hanging cables. When a freely hanging cable is subjected only to its self-weight, it assumes a shape of a catenary. The cable carries forces only in tension along this curve. When the shape is flipped around its anchor points, it creates an arch in perfect compression. Gaudí explored this property of hanging cable models (Figure 5) in his work [11], including his famous unfinished project of La Sagrada Familia in Barcelona, Spain (Figure 6).

Figure 5: Hanging chain model displayed in Barcelona

Figure 6: La Sagrada Familia in Barcelona, Spain

A few decades later, Heinz Isler explored the catenary to create curved surfaces using damp sheets. Isler explored the idea of the catenary to create three-dimensional tension surfaces [12]. His method consisted of hanging wet fabric and letting it freeze (Figure 7). The hanging cloth creates a catenary surface, which, when flipped, could become a structural shell in compression. Isler's method allowed for the creation of very thin and lightweight structures. He became a reference for his pioneer work in concrete shell structures, amongst its well-known projects is a concrete shell that covers the Deitingen Süd service station, built in 1968 in Switzerland (Figure 8).

Figure 7: The hanging membrane model shown in Isler's IASS Congress paper, 1959

Figure 8: Deitingen Süd service station, Switzerland, 1968

Although these approaches lead to simple optimal shapes, they were not suitable for more complex structures. There was an interest in developing methods that could be applied to a wide variety of problems, which could involve different applications, constrains and materials.

With the advance of technology, computers started to become essential tools for engineers. With an increasing processing speed and a larger storage capacity, it was possible to carry out accurate structural analysis based on the finite element method (FEM) [1]. The finite element method (FEM) is a numerical technique originally used for plane stress analysis, particularly for the analysis of aircraft structures.

However, over time, it has been applied to a wide variety of problems in science and engineering, including structural engineering. It consists of the discretization of a continuum domain into a finite number of parts (the finite elements) through the creation of a mesh and finding local solutions within the boundary conditions of each element. By joining all the solutions of each element, a global solution of the complete domain can be obtained.

Although this method had been around since 1940's, it was with the revolution of computer power that they were implemented in order to obtain cheap and fast results [1].

The emergence of these tools and the ever-growing computational speed meant the use of computers was becoming more frequent in all stages of the design process. By the 2000's, packages of design and structural analysis software (which included the implementation of the FEM) were being used by engineers. Currently, these tools are used from early stages – concept design stage (to define the topology or layouts), through preliminary design (shape of the building) and at the detailed design stage (sizing and detailing of structural members).

From this revolution, new concepts started emerging such as computational design. Although it is a relatively new term, it brings along concepts such as parametric design, generative design, and algorithmic design.

Parametric design is the process of describing a design through defined parameters, which can be manipulated in order to change the result. This process was used before the introduction of computers. The previous example of Gaudi's hanging chain model is also an example of parametric design. In this case, the lengths of the cables were parameters, and by manipulating them, Gaudí was exploring different design solutions. Nowadays, there is a variety of software which allow this approach (for the development of this thesis Grasshopper 3d was used).

Generative design consists in developing designs through algorithms which encode the principles of design to generate models without the direct intervention of the engineer [13]. By describing the principles of design (parameters and goals) rather than the specific instructions for one solution we are taking advantage of the computer's ability to explore the design space more thoroughly and generating multiple alternatives of design – which might not had been considered if the job had been done by the engineer as there is a limited of options one can feasibly analyse.

Algorithmic design is the creation of forms through algorithms. In this case the engineer or architect has the ability to create shapes by implementing a set of rules and constraints into the algorithm. It is clear that this concept overlaps with generative design. However, in algorithmic design it is possible to trace the design result back to the algorithm that generated it [13]. There is a correlation between the manipulation of the algorithm and the design result [13]. In generative design that is not necessarily the case.

In generative design, after setting up the problem (parameters, constrains and goals), the generative process starts and continues until it satisfies the stop criterion. The generated output will generally be an array of complex designs that are difficult to correlate with the algorithm that generated it. This is because the algorithms used in generative design introduce some degree of randomness in the search for the optimum (to better explore de design space).

Overall, the concept of computational design brings a change into the design process. Initially the software was created to replicate the design process – there was no fundamental change. Now, with these new concepts, computers are allowed to play an important role in the design process. Rather than being used for traditional design problems of analysing solutions and creating virtual models created by engineers or architects, they are being used to explore, optimise, and generate different solutions from the rules set by the engineer. This means there is an expansion of the solution space – as the solutions considered are no longer limited to the ones engineers and architects create – leading to a wider range of solutions. Engineers and architects have more freedom to analyse different solutions and achieve better designs and, in addition, a more optimal solution.

2.1.2. SETTING UP AND SOLVING THE OPTIMISATION PROBLEM

2.1.2.1. Optimisation Problem

As previously stated, in generative design a problem is solved by following the established principles of design. Nevertheless, some other aspects need to be specified in order to delimit a feasible region which encloses all possible outputs upon a defined set of constrains. Through generative design it is possible to explore a very large number of solutions, which means there is a higher probability of finding an optimal solution.

In the context of structural design, the optimisation problem is set up by creating the design space. The design space, or design domain, is a system which encloses within itself all the unique possibilities of results that populate the solution space. To be effective, when defining the design domain, a clear idea of the outline of the structure should be considered leading to an array of unique designs. In other words, the problem has to be clearly set up. To achieve this, three components must be defined:

- the vector of input data - which contains all the input parameters that create the different alternatives for a solution;
- the objective function - which defines the features intended to maximize/minimize in the optimisation process (the target). An optimisation problem can be defined by one objective function - single-objective optimisation - in which case the problem tends to be simpler to solve and it is usually possible achieve a single optimal solution. However, in most cases (especially in the context of structural design) the problem has more than one objective function - multi-objective optimisation. In these cases, there is the possibility that the optimal results for different functions might be contradictory - which means they will have to compete and arrive to a compromised solution. In alternative, they might return to the engineer and array of optimal solutions from which to choose [9];
- the constrains - they define whether a solution is within the boundary limit of the solution space, and therefore if it should or should not be considered as part of the solution space. In other words, they define the feasibility of a solution.

Based on the above, it is reasonable to say that the design space is a combination of these key features translated into a geometric system (feasible regions of the problem). Usually the process of creating the design space is iterative and can be adjusted to better suit the problem at hands. This geometry is often constructed through parametric design.

2.1.2.2. Optimisation Algorithms

After defining the optimisation problem, the next step is to choose an approach to solve it.

This will be dependent on the nature and complexity of the problem at hands. If a problem is simple, it will likely have a direct solution that is – obtained through solving it according to its objective function. However, most optimisation problems are complex and require the use of optimisation algorithms. These can be divided into two categories: deterministic methods and stochastic methods.

The first category – deterministic optimisation – is characterized by following a rigorous mathematical approach to arrive to an optimal solution [14]. These algorithms are also referred to as mathematical programming due to the employment of linear algebra for gradient-based optimisation.

Deterministic algorithms can be grouped into two types: unconstrained optimisation and constrained optimisation algorithms [14].

In unconstrained optimisation problems the objective function is minimized, and the variables have no restrictions to their values. There are two strategies these algorithms can follow: one is the line-search approach and the other is the trust region approach [14]. Both are iterative processes to reach the minimum of the objective function.

In constrained optimisation problems, the objective function is minimised while constraint functions are defined – one set of equality constraints and another of inequality constraints [14]. There are many techniques that can be applied to solving constrained optimisation problems depending on its characteristics. A common one is linear programming. This technique is used when the objective function and the constraints are linear functions. Other techniques include quadratic programming, non-linear programming, and others which will not be addressed in this study.

Through a deterministic approach it is possible to achieve a result faster than through stochastic methods. Due to its rigorous mathematical basis, deterministic algorithms are very straightforward in the sense that they do not have the randomness characteristic of stochastic methods, leading to results that are unequivocal and replicable [14]. However, this may also lead to results which instead of representing a global optimal solution represent a local optimal. Furthermore, these methods are intrinsically single objective optimization problems.

The second category – stochastic optimisation – refers to algorithms that randomly search the design space for an optimal solution [15]. Most stochastic optimisation algorithms are based on the observation of nature. Concepts from biology, chemistry, physics, and others are implemented into algorithms that create a numerical model which is a simplified and adapted version of natural phenomena with the purpose of solving an optimisation problem [15].

The most well-known stochastic optimisation algorithms are evolutionary and genetic algorithms (EA and GA, respectively), which are widely applied in different subjects, including structural design. In general, EA and GA are population-based algorithms. They simulate the evolution of a population, from an initial set of samples in the design space. The set of samples is called population, and each sample is called individual. From the initial population, the algorithm creates successive generations (the size of the population is constant throughout the process) each better than its predecessor – evolving to a convergence – according to a set of rules [15]. These rules depend on the natural concept the algorithm intends to mimic. For example, in GA the evolution follows Darwin's theory of natural selection.

Setting a clear distinction from the deterministic approach, stochastic algorithms are mathematically less complex and because of the randomness factor are much slower to converge to the optimum solution. Unlike deterministic optimisation methods, stochastic optimisation can be used in multi-objective problems. They are also capable of carrying a more thorough search of the design space, therefore are also able to overcome local optimum solutions – local minima -, and thus allowing for a global optimisation to be achieved.

An important detail that needs to be monitored in these kinds of algorithms is the robustness of the method. The robustness of the method measures the probability of finding the global minimum and can be controlled by setting control parameters that should be carefully chosen in order to improve the accuracy of the solution [15].

There are many stochastic algorithms that are not mentioned in this study, some of them include particle swarm optimisation and game theory optimisation.

2.1.3. Structural Optimisation

Traditionally, structural optimisation can be divided into three types: sizing optimisation, shape optimisation and topology optimisation. The three have different purposes, and, consequently, different problem setups and outputs [8].

Sizing optimisation is the most common type of structural optimisation. It focuses on the optimisation of cross-sectional dimensions and thickness of elements [8].

Shape optimization acts on the geometry of the structure [8] – without modifying its topology – in such a way that it aims to create a shape with uniform distribution of stress and minimize stress concentration.

Finally, topology optimisation is the most general form of structural optimisation – and the one which will be studied in more detail throughout the thesis. It is the most general type of structural optimisation, dealing with the distribution of material in a design domain in order to obtain the best structural performance. A variation of this is layout optimisation applied to frameworks.

2.1.4. TOPOLOGY OPTIMISATION

A generic topology optimisation problem consists of setting up a design domain and generating a geometry that reflects an optimum distribution of material for a structure based on mathematical rules. More formally, it consists of finding a material distribution that minimizes an objective function F, subject to a volume constraint $G0 \leq 0$ and M a characteristic the solution must satisfy (usually the maximum amount of material) [16]. Material distribution is a problem variable specified through a density function of the material, $\rho(x)$, in each location of the design domain – it can be 1 (solid material) or 0 (void) [16].

Topology optimisation has been widely studied throughout the years. Amongst the most used methods to perform this type of optimisation are: Solid Isotropic Material with Penalisation (SIMP) and Evolutionary Structural Optimisation (ESO) [16]. Both techniques involve the discretization of the design domain and the conduction of FE analysis.

SIMP is a technique which uses the density of the material to define the topology. SIMP can be divided into two approaches: minimum compliance design and minimum weight design [17].

In ESO the structure converges towards an optimal solution through the elimination of inefficient elements (or by also adding them, in which case it is called Bi-directional Evolutionary Structural Optimisation - BESO) [16].

The first proposed solutions for topology problems were introduced by Michell (1904) in his paper "The Limits of Economy of Material in Frame-structures" [18] where he shows a series of analytically defined trusses as the materially optimal solutions upon their set of constrains. These optimal trusses became known as Michell Trusses (Figure 9) and are a reference in topology optimisation – they are often used as a benchmark for topology optimisation software.

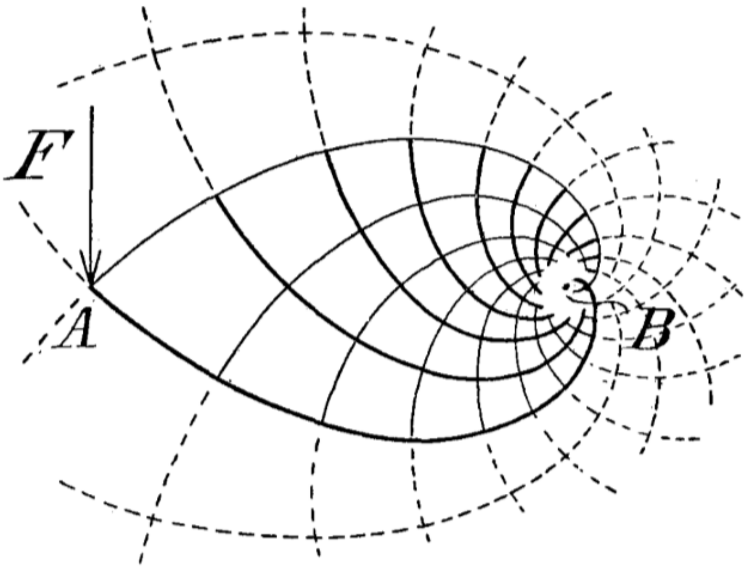


Figure 9: Example of a Michell Truss from his paper "The Limits of Economy of Material in Frame Structures", 1904 [18]

2.1.5. LAYOUT OPTIMISATION

Layout optimisation is applied to frameworks. Like topology optimisation, layout optimisation is a numerical approach that is used to create an optimal frame structure with the optimal distribution of material (in this case, through the elimination of unnecessary members and finding the optimal node location [11]). Typically, a layout optimisation problem starts by defining the design domain, which is then discretized through the creation of nodes that populate the design domain. Throughout the optimisation process, different arrangements are generated by creating potential connections between the nodes (ground structure) until it reaches to the most efficient layout [2].

Although these types of optimisation lead to the most materially efficient designs, they are not very common in the structural engineering practice. The output solutions are usually too complex (number of elements, joints, and different cross-sections) and would not be appropriate in terms of buildability [9]. It is very unlikely that through these methods one can find both a simple and materially efficient solution. However, a good approach would be to rationalise optimum outputs in order to turn them into good solutions to be implemented [9]. Studies show that structures with a similar form to the correspondent optimal solution have the potential to establish a good compromise between material efficiency and structural simplicity [9].

2.2. CARBON FIBRE REINFORCED POLYMERS

2.2.1. OVERVIEW

Carbon fibre reinforced polymers (CFRP) are part of the fibre reinforced polymers (FRP) category. These can also be referred to as "composite materials" or "composites" which means they are the product of the combination of two or more materials with different properties [10]. The result is a new material with its own characteristics, in which the initial individual components remain separate and distinct.

FRP are the resulting material from the combination of fibre reinforcements and polymer resin. The fibre reinforcement is responsible for the mechanic properties of the FRP (load-carrying capacity and stiffness) while the polymer resin defines the shape, serving as a stabiliser, and protects the fibres against UV radiation and aggressive environments (moisture and chemicals) [19]. The most used are glass fibre reinforced polymers (or GFRP), and carbon fibre reinforced polymers (CFRP).

2.2.2. Background

During the Second World War the production of polymers suffered a great boost as the products was being used to supply the army for building tools for the war efforts (parachutes, cockpits for bombers, etc). The production of polymers increased massively, but once the war was over the use of these capacities was shifted towards the production of everyday products. Soon enough polymers were entering new markets, and they were being used in the production of common household items, packaging, etc.

The first application of polymers in buildings was in the construction of enclosures for radar stations using GFRP. The use of metals was avoided in order to prevent the disrupting of the electromagnetic signals. The first enclosure was built in 1955 on Mount Washington, and several others followed [10].

In 1954 the Massachusetts Institute of Technology (MIT) and Monsanto Chemical Company worked together in the development of a house completely made of polymers [10]. In 1957 the prototype was built in "Disney World". It was a representation of what a "house of the future" would look like. During the 1960's many more prototypes of polymer houses were built. Some argue the most iconic is the "Futuro" house by Matti Suuronen (1968) [10], shown in Figure 10. This house reflected what was happening in the world at the time being inspired by the evolution of technology and space travel. Polymer houses became associated with the futuristic visions of that time.

Figure 10: Futuro house in Finland, 1968

The experimentations with polymer houses came to a halt with the first oil crisis (1973) [10]. The rise in the price of raw material allied with new environmental awareness were determinant factors for the abandonment of ideas of polymer houses.

Nowadays, most applications of polymers can be found in automobile and aircraft industries, as fibre composites have a high strength-to-weight ratio it is possible to achieve great performance due to weight savings (e.g.: reducing the power necessary to make a plane fly). There are some applications in the building industry as well. However, there are not many applications in loadbearing structural elements – some well-known uses of CFRP are for the repairing and strengthening of concrete elements [19].

Nevertheless, new ideas in architecture and the exploration of more complex forms might be reawakening the interest in FRP due to possibility of refining the material properties according to the needs of the designer and the ability to mould the material in order to match complex geometries. The use of these materials in loadbearing structures is still finding its way into the industry.

2.2.3. Components

Fibre reinforced polymers are the result of adding fibres to a polymer. This combination, as previously stated, creates a new material with its own characteristics. To understand them, it is essential to know the properties of the fibres and polymers involved in the combination. There is a wide array of polymers and fibres to choose from so it is important to understand how each type will change the outcome of the composite.

2.2.3.1. Polymers

Manufactured polymers are synthetic materials made through the assembly of individual molecules (monomers) to form macromolecules (polymers). They can be divided into three categories according to the way the molecules are linked. Polymers can be thermoplastic, elastomers and thermoset [10].

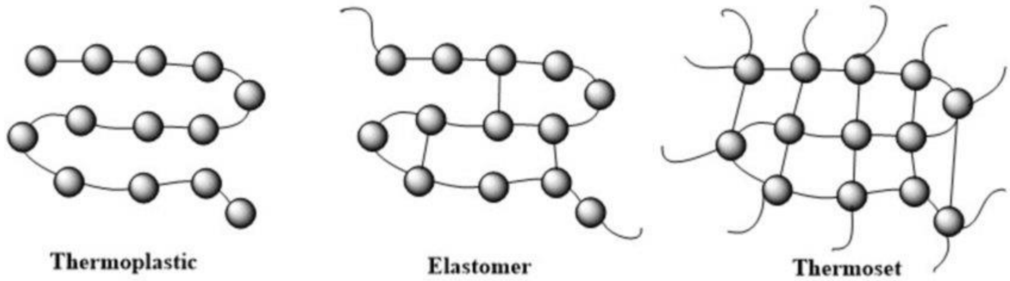


Figure 11: Schematic image of the linkage between monomers in the three types of polymers [20]

In the first case the molecules are not cross-linked and have low strength and low heat resistance – they can be melted and reshaped more than once [10]. In the second category the molecules are cross-linked thereby they cannot be melted again after being produced. They also have low strengths. Finally, in the third category, the molecules are cross-linked – making them able to achieve high strengths – and, like elastomers, they cannot be melted again after being produced [10].

In the construction industry, engineers tend to opt for stronger and more durable materials that are resistant enough to be able to withstand large stress levels. Among the three types of polymers, thermosets are usually the ones chosen for structural application due to its high strength and durability.

Unlike most materials used in construction (e.g.: concrete, steel), polymers have the flexibility of adapting its properties according to design requirements [10]. Traditional materials can vary their properties of strength and shape within a narrow scope of options. However, polymers have a wider range of possibilities available in order to adapt to the demands of a particular structural requirement. This puts them in an advantageous position in comparison with other materials.

The process of changing properties of polymers is done during production through the addition of fillers and additives to the basic material in manufacturing [10]. Additives are substances that improve the properties consequently improving the polymer's performance (e.g.: fire retardant in order to improve the fire resistance behaviour) [10]. Fillers are used to extend the polymer, with mostly no impact in the properties, they are essentially used to reduce the costs of raw material.

In short, most polymers are made from petrochemical processes (meaning that the raw material is crude oil), which involve the heating of the oil in a refinery, dividing it into fractions. The fraction called naphtha (10% of the whole product) will later originate the polymers [10]. The assembly of monomers occurs through one of three chemical processes: polymerisation (the linkage is done with introduction of catalysts and there are no by-products being produced), polycondensation (phased chemical reaction with water as a by-product) and polyaddiction (also a phased reaction, but does not produce by-products) [10]. During manufacturing additives and fillers are added in the process. The primary products of the global procedure differ in the shape of the output. The primary product of thermosets is synthetic resin to which is added a hardener that reacts with the resin to create the cross-link.

The chemical structure of thermoset polymers results in a set of properties – strength, durability, and chemical resistance – which make them ideal for the combination with fibres in order to create FRP composites.

Despite being more expensive, epoxy resins are amongst the most used thermosetting polymers across industries. Its most common applications in construction include structural adhesives and the creation of the resin matrix for FRP composites [21].

The popular choice of epoxy resins for composites is based on its good mechanical properties and high durability in service. Epoxy resins are characterised by high adhesive strength which is very convenient in the creation of FRP composites as it allows the resin to adhere onto the fibres used for reinforcement [21]. Other favourable aspects of epoxy resins include low shrinkage rate in curing, compatibility to most manufacturing processes and low emission of toxic products during curing [21]. Furthermore, epoxy resins are resistant to chemicals and corrosion providing good protection for the fibres embedded in the resin matrix of FRP composites.

Nevertheless, there is an aspect that needs to be considered when working with epoxy resins – brittleness. Epoxy resins have a brittle behaviour, which is not ideal in construction where ductile behaviour is usually sought. However, and following the principle that it is possible to adapt the properties of polymers as convenient (albeit within certain limitations) this aspect is usually solved by adding small amounts of liquid rubbers with highly reactive terminal carboxyl groups [21]. The rubber bonds with the epoxy matrix increasing elongation at break, thus preventing the propagation of cracks in the matrix [21].

2.2.3.2 Fibres

Fibres are a kind of material with a thread-like structure. They can be found in nature (e.g.: human hair), or they can also be man-made (e.g.: carbon fibre). Fibres are often the base material for more complex structures. They can be classified as inorganic fibres, polymer fibres, metal fibres or natural fibres. All man-made fibres can also be called synthetic or chemical fibres. Overall, they usually come in bundles of very thin filaments (synthetic fibres are thinner than human hair). A bundle of parallel filaments is called roving (Figure 12). To identify the number of filaments that are present in a roving it is usually referred as kilo (1000 fibres is equal to 1K). Rovings are the raw material used in FRP [10] (Figure 13).

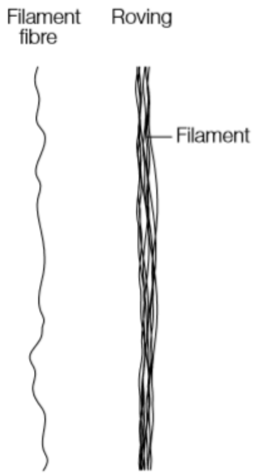


Figure 12: Correlation between a filament and a roving. Adapted from 'Construction Manual for Polymers + Membranes' [10]

Figure 13: Carbon fibre rovings are usually sold in tows

For structural application, synthetic fibres are often the best choice when compared to natural fibres as they are stronger and more durable. The process of synthesizing fibres is responsible for its mechanical properties. In this process the raw material that ultimately originates the fibres is melted and stretched aligning the internal structure of the fibre [10]. This translates in an increase of strength. The smaller the diameter, the stronger is the fibre. Furthermore, as the stretching occurs in a particular direction, as the fibres get stronger longitudinally, its mechanical properties decrease transversely.

To create FRP composites, the most frequent choices are carbon fibres and glass fibres. The two main aspects that are considered in the choice are the tensile strength of the fibre and its elastic modulus (E). This last one being the most important. To produce fibre-reinforced polymers the fibres are embedded in a polymer – creating a protective matrix for the fibres. As it was previously referred, thermoset polymers suffer from very low elongation after curing, as such, to choose the type of fibre to use, it is important that it has a high elasticity modulus, and therefore minimum deformation. Otherwise, if the fibre were to elongate beyond the capacity of deformation of the polymer, it would result in the cracking of the matrix. For this reason, the elastic modulus is the determinant factor to choose the fibres [10].

Glass fibres and carbon fibres have very similar tensile strengths. However, the elastic modulus of carbon fibre is much higher than that of glass fibre [19]. This means that even though the tensile strengths are similar, carbon fibre is stronger when embedded in the polymer matrix (with its limited deformation capacity). Regardless, it is important to mention that this does not mean carbon fibres are always the best option as it always depends on the requirements of the FRP component.

The properties of carbon fibre can still vary greatly in regard to tensile strength and stiffness. Three forms of this fibre can be produced: standard modulus fibres (high tensile, HT) with high tensile strength, high modulus (HM) fibres with high material stiffness and intermediate modulus (IM) fibres with moderate tensile strength and material stiffness [10]. Unlike glass fibre, carbon fibre is an anisotropic material showing an inferior performance of stiffness and strength in the transversal direction of the fibres. In addition, the coefficient of thermal expansion is positive in the transversal direction and negative along the fibres [10]. Two potentially problematic characteristics are the sensitivity to buckling – which can be solved in FRP through the polymer matrix – and its brittleness. Nevertheless, carbon fibres are a quality choice for FRP.

2.2.4. CARBON FIBRE REINFORCED POLYMERS

After discussing the properties of polymers and fibres separately it is now possible to evaluate the resulting material that is CFRP.

Carbon fibre reinforced polymers or CFRP are composite materials made of carbon fibre filaments embedded in a polymer matrix, which, in this particular research, is epoxy resin. The two components complement each other resulting in a high-performing material [10]. With its high strength and stiffness, the fibre component is responsible for the load-carrying, while the polymer matrix transfers the stress between the fibres. Also, the polymer matrix provides protection to the fibres against external factors and gives the CFRP composite its shape. One particular weakness of carbon fibre is its sensitivity to buckling. At the same time, the thinner the fibre, the stronger it is. This paradox is solved through the introduction of the polymer matrix. It serves as a stabilizer for the fibres. Ultimately, the composite material ends up being able to carry compression loads to a satisfyingly high degree without having problems of instability. This results in material characterized by its high tensile strength, high stiffness, low density, and high chemical resistance. Figure 14 show the stress-strain diagrams for several materials used in construction including CFRP and GFRP clearly showing their brittle behaviour when compared to structural steel, but also their high-strengths.

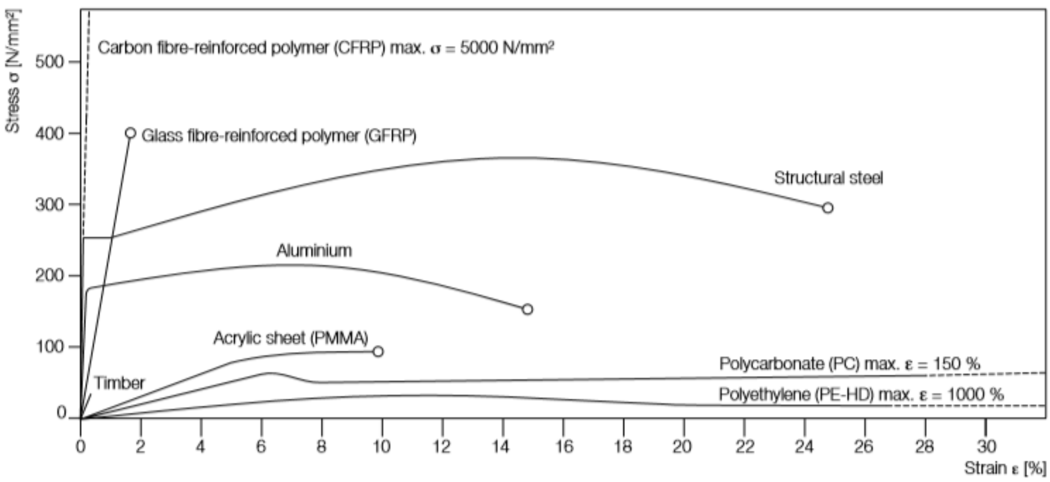


Figure 14: Stress-strain diagram of composite materials in comparison with traditional material used in construction. Adapted from 'Construction Manual for Polymers + Membranes' [10]

Since composites are the direct product of the combination of two different materials, their properties can vary greatly depending on the conditions at which they are produced. There are two approaches to determine the mechanical properties of a CFRP composite: experimental characterization through testing samples of the material– that falls outside the scope of this study – or through a theoretical approach. A rule of mixtures can be applied to determine most of these properties [22].
The rule of mixtures is a weighted mean approach to determine properties of the resulting material – in this case CFRP [22]. This method uses the properties of the individual components – epoxy resin and carbon fire – and the proportionality of quantity of each component. For example, to determine the elastic modulus of CFRP (E_{CFRP}) based on the volume of each component:

$$E_{CFRP} = E_f V_f + E_m V_m \text{ , with } V_f + V_m = 1 \quad (1)$$

Where: E_f is the fibre modulus of elasticity; E_m is the matrix (epoxy resin) modulus of elasticity; V_f is the fibre volume ratio, V_m is the matrix volume ratio.

With its favourable properties and the different shapes it can adopt, CFRP composites have had some applications in the construction industry. Particularly in the strengthening and rehabilitation of structures (made of steel or concrete) with CFRP elements, taking advantage of their high strength and stiffness. These CFRP composites are usually produced in textile membranes that are wrapped around the element (Figure 15) that needs strengthening (e.g.: concrete columns or beams). They can also be produced in the form of rods that can be added to concrete elements as reinforcement.

Figure 15: CFRP fabric wrapped around beams

The unidirectional aspect of CFRP composites has also been seen as a good potential alternative for steel cables in cable structures. Actually, the first application of CFRP cables in a cable-stay bridge (Figure 16) was in Stork Bridge in Switzerland [23].

Figure 16: Stork Bridge in Switzerland, completed and opened to traffic in 1996

3
CASE STUDY: CARBON FIBRE CANOPY

3.1. OVERVIEW

3.1.1. BRIEF

3.1.1.1 Introduction

The following brief has the purpose of describing the study carried out for the conception, design and construction of a canopy using carbon fibre reinforced polymers (CFRP).

This exercise in carbon fibre aims at the development and application of a suitable workflow for the design of structures using CFRP, while also applying optimisation techniques to reach an efficient solution for the geometry of the structure.

The optimisation tool applied in this project was Peregrine [2], a plugin for Grasshopper [3]. Peregrine is a layout optimisation tool that creates an optimised truss-like geometry for a given design domain and set of loads, supports and material properties. This plugin is particularly suitable for this project considering that the results come in the form of lines which match the unidirectional nature of the material to be used (rovings).

3.1.1.2. Site and Design Boundaries

The construction site is located in Walcot Street (Bath, UK) in the offices of Format Engineers, shown in Figure 17. The main purpose of this structure is to provide shelter for bikes. However, it could potentially be used as a communal space for the company's office as well.

Figure 17: Walcot Street, Bath, Uk

By knowing the location of the site and the usage intended for the canopy it is already possible to define all the loads that should be considered in the design: self-weight, snow loads and wind loads.

The design space for this case study is influenced by the site's boundary constraints. The back garden is bounded by two walls and a fence. One of the walls is going to be used as the fixing surface for the structure. Most of the available space can be covered by the canopy. Nevertheless, there are some limitations to account for: there is a small area in the corner where the two walls meet, and the structure cannot interfere as pipes are running along this intersection (Figure 18 and Figure 19).

Figure 18: Pipes in the intersection of the walls is part of the boundary constraints

Figure 19: Pipe running along the intersection

Another aspect to consider is the height above the ground at which the canopy will be fixed. Although the structure is intended to be a shelter for bikes, it should be designed to allow people to stand comfortably underneath.

Therefore, a reasonable space of area to cover was defined: an area of 4 m wide and 2 m length, as demonstrated in Figure 20.

Figure 20: Covered area by the canopy

3.1.1.3. Scope

The scope of this study focuses on four main aspects: topology optimisation tools, design domain, material properties and fabrication processes. Accordingly, after the initial survey of the site, a first phase of topology optimisation occurred to choose the most suitable software, followed by the initial setup of the design domain. Which was successively refined towards the best possible representation of the real problem. Together with the design domain, the material properties of CFRP rovings were evaluated and used as an input parameter in the optimisation problem.

The outcome was a set of different geometries within the considered solution space. All the solutions were compared, and a choice of the optimal solution was made – the optimisation parameters were the amount of material (CFRP rovings) required and the complexity of the final geometry.

Finally, a proposal for the fabrication process that matches the geometry and material will be presented in chapter 4.

3.1.1.4. Assumptions

In order to establish a clear and consistent starting point for this study, some assumptions have been made:

- The canopy will be designed as a modular structure (to simplify the fabrication setup and to facilitate the adaptation to time constraints), and throughout the study only one module will be considered (as the others will be replications)
- The canopy will be a cantilever structure
- The material to be used for the load bearing structure are CFRP rovings
- Uplift wind is the dominant force acting on the structure
- Even though in reality the roof panel will have a slope as required, in every model the slope of the roof panel will be zero in order to simplify the calculations of the software – as it is a lightweight structure and the slope is relatively small the impact will not be relevant.

3.1.1.5. Software for structural optimisation

As it has been mentioned, there is a great variety of software for the purpose of structural optimisation. This particular project was developed in Grasshopper – a parametric design tool that allows designers to generate geometry based on rules described using its visual programming language, it also supports standard programming languages such as C# and Python.

For the purpose of topology optimisation, several plugins were tested with the intent to find the one that best suited the material properties of CFRP rovings. The plugins assessed include: Ameba, Millipede and Peregrine. Accordingly, the software should allow the user to set the mechanical properties of the material (elasticity modulus, tensile strength, compressive strength, Poisson's ratio, etc), and also should be able to replicate the unidirectional nature of the CFRP rovings.

To test each plugin, a 2-dimensional simply supported beam (Figure 21) problem was set up. A beam of 18.7 m by 1.5 m subject to 1.5 kN/m^2 of imposed load (IL) and 4.75 kN/m^2 of super dead load (SDL) was considered, as illustrated in Figure 21:

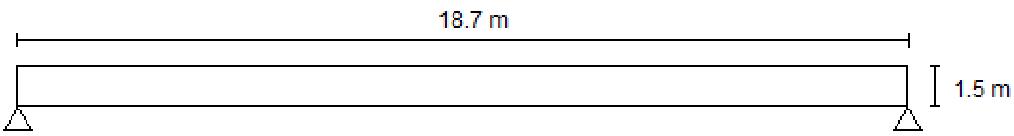


Figure 21: Simply supported beam

The results of topology optimisation in a simply supported beam were the following geometries (Figure 22, Figure 23, and Figure 24:

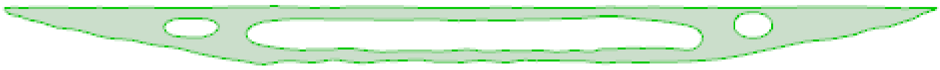


Figure 22: Result from Ameba

Figure 23: Result from Millipede

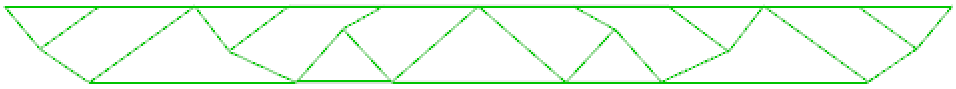


Figure 24: Result from Peregrine

Analysing the results, the difference between topology optimisation and layout optimisation becomes clear. In the first two plugins, the resulting geometries show the optimum distribution of the material creating holes (or voids) where no material is needed – as previously described, this outcome is characteristic of topology optimisation. The two plugins are for topology optimisation, it is also clear that the resulting geometries show some resemblance. However, they are not exactly the same. This is due to the different processes within topology optimisation. In the third result (Figure 24), the nature of the geometry is different from the others. In this case, instead of a continuum domain with different density of material, the result is discretized in a frame structure composed by bars and nodes – characteristic of layout optimisation. This kind of geometry was the one that best translated the unidirectional nature of CFRP rovings, as it was intended for the model of the carbon fibre canopy.

Since the material of choice are CFRP rovings, using Peregrine is the most convenient option as it is possible to take advantage of the discretized nature of its solutions. The bars show the exact position the rovings must occupy within the structure. In addition, it also allows the user to set the mechanical properties for the material. This means Peregrine satisfies all the requirements previously set.

In summary, the theory behind Peregrine is based on the layout optimisation formulation proposed by Dorn et al. (1964) later adapted by Gilbert and Tyas (2003) in which a 'ground structure' is created as a reduced version of the problem with only potential members and gradually adds new ones as required [2]. The objective function is to minimize the total volume material of the final geometry. [2]

$$\min V = l^T a$$

$$\text{Subject to} \qquad (2)$$

$$for\ all\ \alpha \in \mathbb{F} \begin{cases} Bq^{\alpha} = f^{\alpha} \\ -\sigma^{-} a \leq q^{\alpha} \leq \sigma^{+} a \end{cases}$$

$$a \geq 0$$

Where V is the structural volume; l and a represent the vectors of length and area of each element; B is an equilibrium matrix composed of direction cosines; q is the vector of internal forces on each bar-element and f the vector of external forces; σ^{-} and σ^{+} are the compressive and tensile stress limits, and $\mathbb{F}$ is the vector of load cases.

3.2. Geometry Study

3.2.1. Defining the design domain

For the design space of a singular module of the canopy, two alternatives were considered: a rectangular prism (Figure 25) and a triangular one (Figure 26). In this first stage, the goal was to understand how small changes in the design domain would impact the overall topology of the solutions given by Peregrine.

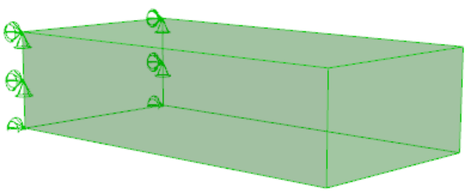


Figure 25: Rectangular prism as the design domain

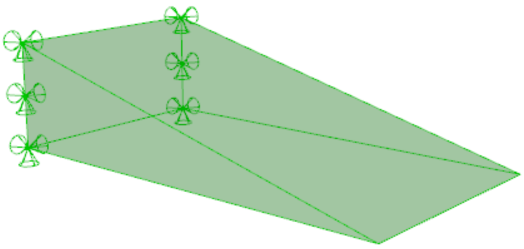


Figure 26: Triangular prims as the design domain

For each domain, the same load cases were applied (a constant surface load representing the actions on the roof panel), and a first set of models was created in which the following parameters were changed:

- Number and position of supports – if we feed Peregrine with a group of potential support points, it only uses the ones it needs to create the optimal geometry, ignoring the remaining ones.
- Height (h) of design domain – the values for h ranged from 0.3m to 1.0m. This value would dictate the size of the plane in which the support points can be located.

- Angle (regarding the triangular domain) – this refers to the angle formed between the cantilever length and the wall plane. Changing this value will change the slope of the triangular prism.
- Position of the load surface – the position of the load surface will dictate the place of the roof panels as they will be the ones subjected to most of the loading cases (wind, snow, etc).

There are a few remarks worth referring from this first series of results. Regarding the number and position of supports, given the load cases for this stage, the usual number of supports were 4 (one in each corner of the plane) or 6 (4 in the corners and 2 in the intersection of the surface load and the support plane).

As the height of the design domain increases, the shape goes from being a structure with trusses on the sides converging in the middle creating a flat geometry (Figure 27), to a structure that, while maintaining the side trusses, converges in the middle creating a curve. Resulting in a structure excessively heavy and complex (Figure 28).

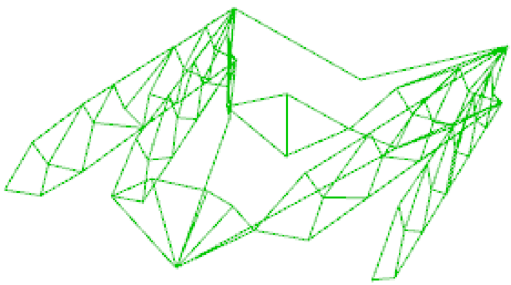


Figure 27: Resulting geometry with *h*=0.3 m

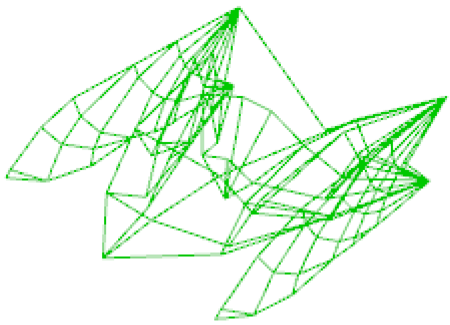


Figure 28: Resulting geometry with *h*=0.6 m

As previously stated, the location of the load surface indicates the place for the roof panels in the structure. This parameter combined with the changing of the angle is a good indicator of how the structure will work as a whole. This is especially interesting as we are working with carbon fibre which is known to have an excellent performance in tension. For this reason, and given that the dominant load comes from the uplift wind, it was concluded that the best shape of the design domain would be one with the angle correspondent with the roof panel at mid-height or at the top.

Considering all these observations, the design domain was adjusted, and a new set of models was created. In these new design domains: the two alternatives of prims were kept (the triangular prism – Figures 29 and 30 – and the rectangular prism – Figures 31 and 32); the roof panel was considered to be at the middle or at the top; 4 support points were considered and the maximum height of the shapes was 0.5 m. These characteristics can be confirmed in the following images:

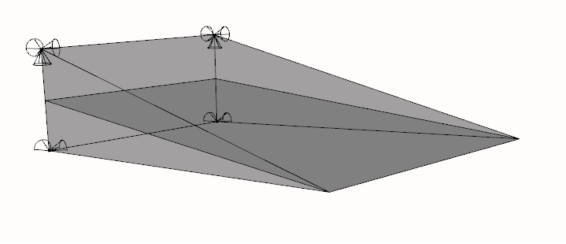


Figure 29: Triangular domain with load surface in the middle

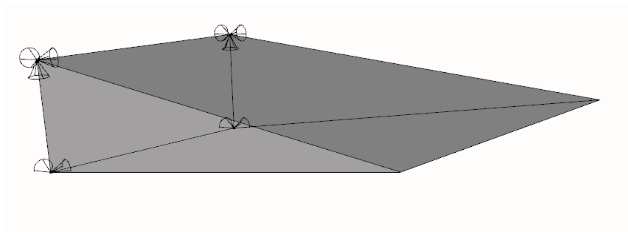


Figure 30: Triangular domain with load surface at the top

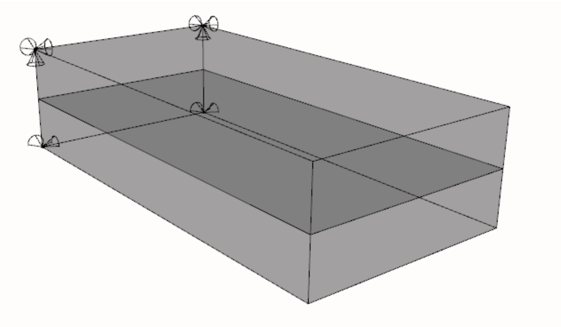


Figure 31: Rectangular domain with load surface in the middle

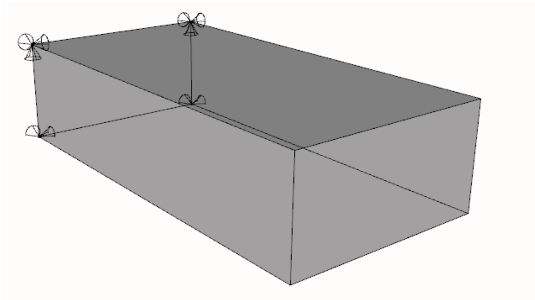


Figure 32: Rectangular design domain with load surface at the top

This second set consisted of four different results – the geometries can be found in Annex 1. By analysing the geometries, it is possible to point a common characteristic: their complexity. It becomes clear that the degree of complexity is too high with too many nodes and bars. This has implications in the time it takes for the optimisation to be completed as well as in the more advanced stage of construction. To solve this issue new adjustments to the design domains were made.

The first was in the load application. In the previous models, the loads were being applied as surface loads. This did not represent accurately the way this structure was intended to work. The loads should be applied to the roof panel, which then carries the forces to the carbon fibre structure through the connections on the panel.

The inclusion of these connections brought attention to another aspect of the models: the intersection of the carbon fibre structure with the roof panel. By assuming the position of the connections, it is ensured that the carbon fibre intersects the panels in those specific positions. However, if the domain considered in the model is continuous there is no way to control the number of intersections (besides the ones that are imposed) of the fibres with the roof panel. This would pose a problem in the construction phase as it would mean holes would have to be introduced in the panel to allow these intersections – this situation would make the construction process more difficult. For this reason, in the models that assume the roof panel to be placed at the middle, the domain was divided into two parts: top and bottom.

3.2.2. GEOMETRY MATRIX

Following the latest adjustments, the design domain was deconstructed into parameters, as shown in Figure 33:

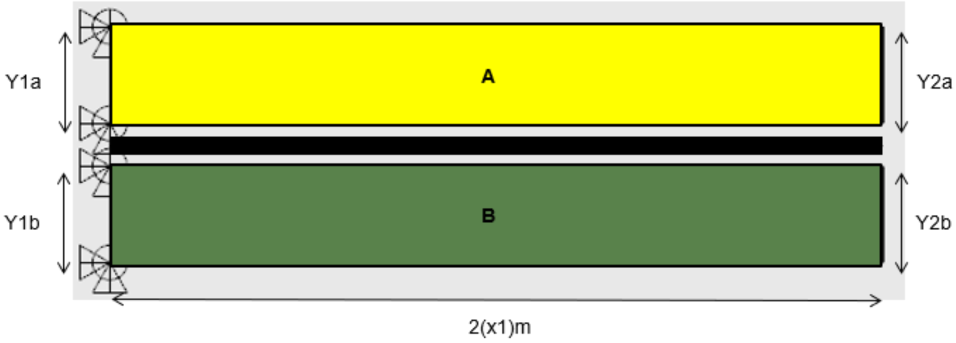


Figure 33: Deconstruction of the design domain into parameters

By breaking down the geometry into parameters it is possible to enclose all the possible design domains while maintaining a logical connection between them. The prism is divided into top (A) and bottom (B), and the variables that encode the different shapes of the prism are Y1a, Y2a, Y1b and Y2b. These variables are discrete and can be assigned the following values (Figure 34):

	Variables	Values		
A	Y1a [m]	0	0.25	0.5
	Y2a [m]	0	0.25	0.5
B	Y1b [m]	0	0.25	0.5
	Y2b [m]	0	0.25	0.5

Figure 34: Values each variable can be assigned

There are a few conditions that must be respected. The previously stated constrains regarding the most favourable shapes (roof panel at mid hight or at the top) were maintained. The new condition consists in not considering the cases in which Y1a was zero and Y2a was not, and the same for the cases with Y1b zero and Y2b not zero. These solutions would not make sense structurally.

To summarize the solution space provided by this problem setup, a geometry matrix was created, as shown in Figure 35:

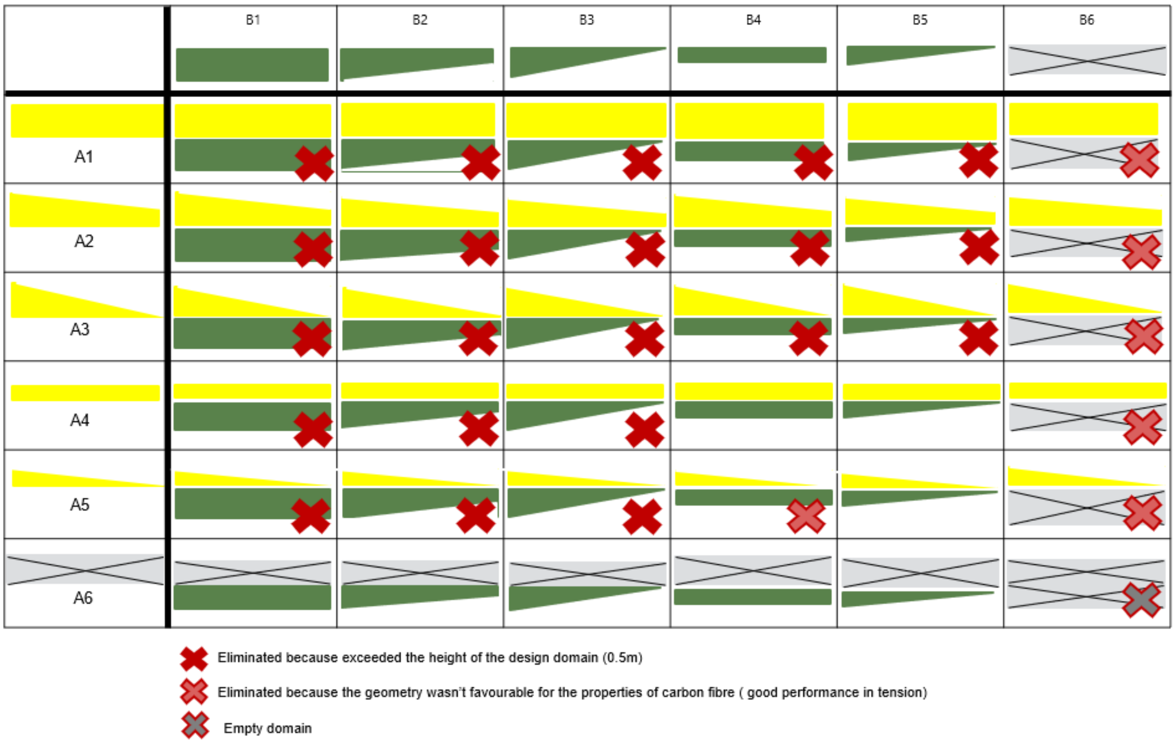


Figure 35: Geometry matrix, used to select the design domains to consider

These options went through an elimination process and the ones that either did not respect the design domain limits (height over the 0.5 m allowed), or the shape was not favourable for the properties of CFRP were discarded. Ultimately, eight domains were chosen (Figure 36). Each domain was used to produce two variations of geometries – in one domain there were four connections on the roof panel and on the other, there were six. In total, the array of geometry options consisted of sixteen solutions.

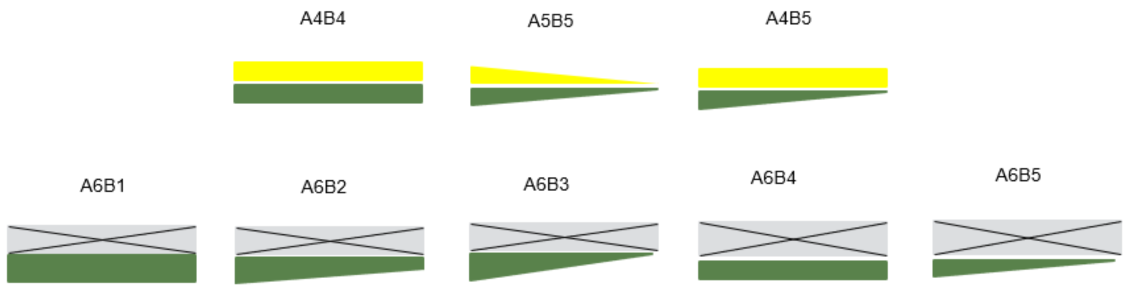


Figure 36: Final domains considered

3.2.3. PEREGRINE MODELS

Once the sixteen domains were selected (refer to Annex 2) the optimisation problem was introduced in Peregrine. For each model it was necessary to input the design domain, including load cases, and material properties.

For each of the sixteen options, the geometry was defined. In order to simplify the process of optimisation, only one side of each shape was represented taking advantage of their symmetry. This way, the solver optimised half of the structure providing a faster delivery of results and ensured that the output was a symmetrical geometry.

One of the biggest issues with working with CFRP is the potential occurrence of buckling. Currently, Peregrine is not able to include a buckling check in the optimisation process. To work around this issue, an estimate critical stress was calculated and used as the compressive stress limit. For this, an average length was used (calculated by creating the models using typical CFRP properties in tension – 2800 MPa – and 90% of this value in compression – 25520 MPa). With this length (L_e = 0.329 m), and assuming a cross-section of 2 rovings the Euler critical buckling stress was determined. This value was used as the compressive stress limit input for the generation of the final models. This stress is a simplified approach at including a buckling analysis into Peregrine, as such it disregards the influence of geometric imperfections. In this study, the material properties of CFRP correspond to those of intermediate modulus fibres (IM). [10]

$$P_E = \frac{\pi^2 EI}{L_e^2} \tag{3}$$

$$\sigma_e = \frac{P_E}{A} \tag{4}$$

The stress was used as an input in the material set up, Figure 37.

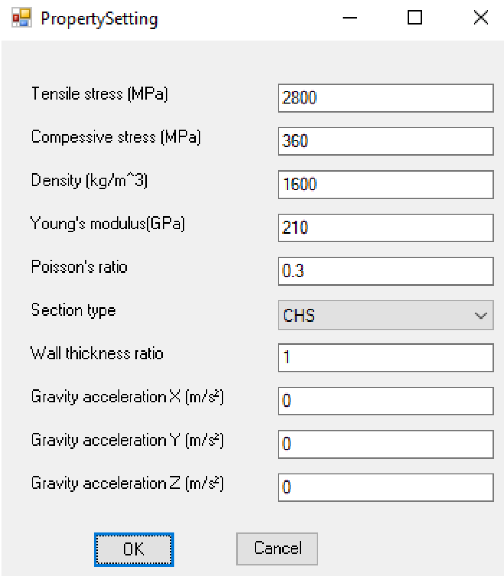


Figure 37: Material set up in Peregrine

Regarding the loads, four different load cases were created, each consisting of a unit point load. Two cases in which the point loads were applied vertically in opposite directions and two others were applied horizontally, also in opposite directions. The vertical ones represent the self-weight of the structure and downwind (applied downwards), and upwind (applied upwards), Figure 38. The horizontal loads represent the effect of sidewind one in each direction. In Peregrine the magnitude of the loads only influences the cross-section area, while the direction is responsible for the resulting geometry. The use of Peregrine was to obtain the geometry as the design of the cross-sections would be carried out using Karamba3D. Thus, the use of unit point loads.

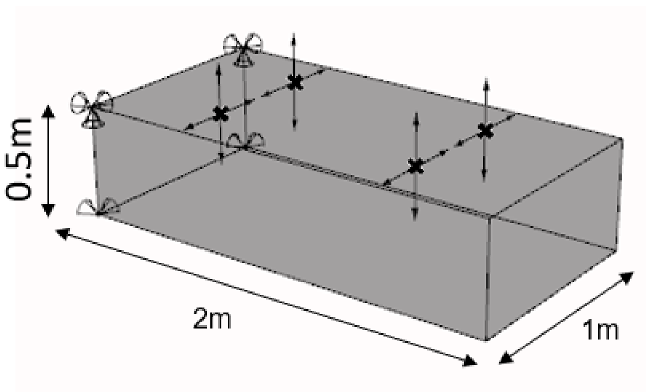


Figure 38: Peregrine load cases applied to domain A6B1

After setting the geometrical domain, the load cases and the material properties, these parameters are connected to the linear programming (LP) solver. The LP solver is responsible for discretizing the domain through populating it with nodes, and then carrying out the layout optimisation process generating elements that connect the nodes forming the ground structure previously referred. The output is a geometry of the most efficient element layout.

These first solutions are often composed of very thin elements and a geometry too complex to be built. For this reason, the first solutions go through a rationalization process. The rationalization component in Peregrine tries to simplify the solutions provided by the LP solver through moving the joint position and reducing the volume of the structure.

3.2.4. KARAMBA MODELS

The next phase of the study was completed using Karamba3D. Karamba3D is also a plugin for Grasshopper, and it was chosen due to its ability to perform structural analysis providing a range of components that allows the user to define a more detailed representation of structural problems. Karamba3D is also useful in combining parametric design with optimisation algorithms, to obtain accurate results through finite element analysis. An overview of the script developed for the analysis of the canopy is shown in Figure 41.

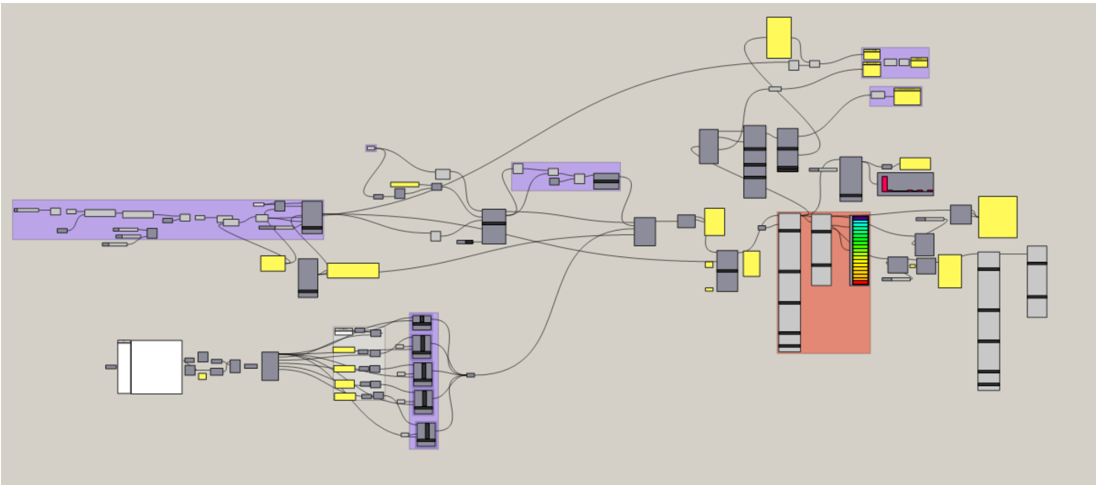


Figure 39: Overview of the Karamba script used in this project

After optimising the topology of the structure and obtaining several options for geometry, the cross-section optimisation component of Karamba was used. As a result, the canopy would go through two different processes: layout optimisation in Peregrine followed by a cross-section optimisation in Karamba3D. In this way, a geometry was generated that minimized the number of elements that composed the structure (results from Peregrine), and then the cross-sections would dictate the amount of material to be used.

To apply the cross-section optimisation, a model of the global structure must be defined. This model should include the elements that compose the structure (geometry), the support conditions, loading, cross-section options and material properties. This information is assembled in Karamba through the 'Assemble Model' component to generate the model, Figure 40.

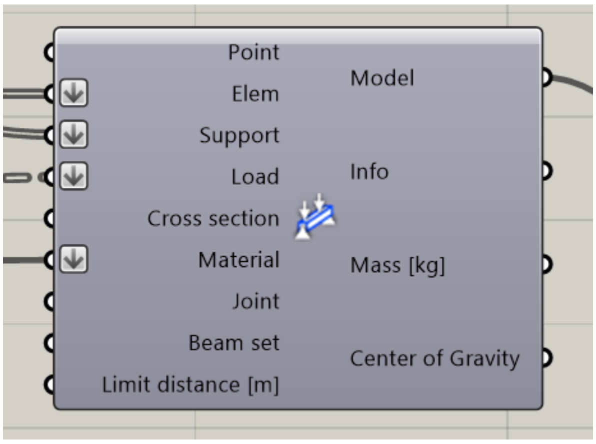


Figure 40: 'Assemble Model' component in Karamba

In regard to the geometry, the output from Peregrine (as bars that define the layout of the structure) was introduced in Karamba converting bars into beam-elements through the component 'Line To Beam', Figure 41. This component was responsible for defining the properties of each beam-element in the structure – including materials and cross-sections.

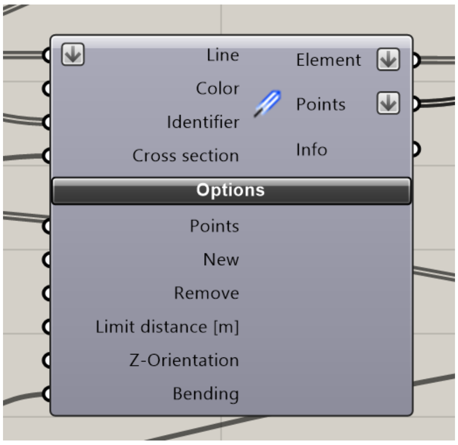


Figure 41: 'Line To Beam' component in Karamba

In defining the material properties of CFRP, information gathered in other projects was used [24]. As already mentioned in this research, the process of fabrication of CFRP involves combining carbon fibres with a polymer (in our case, epoxy resin). The conditions at which this combination is made, has an influence on the properties of the CFRP. For this reason, and in order to generate models closer to the real conditions, properties of CFRP obtained from previous projects were used. These properties include the elasticity modulus (E), in-plane shear modulus (G12) and transverse shear modulus (G3), specific weight (gamma) and yield strength (fy). Even though CFRP is an anisotropic material, as it is being used in rovings – and as a result of layout optimisation the members are working mainly in tension/compression, which means the predominant forces are being carried in the longitudinal direction of each member – only the longitudinal properties are relevant. Thus, to simplify the model, the material was defined as being isotropic. The definition of the material properties in Karamba is shown in Figure 42.

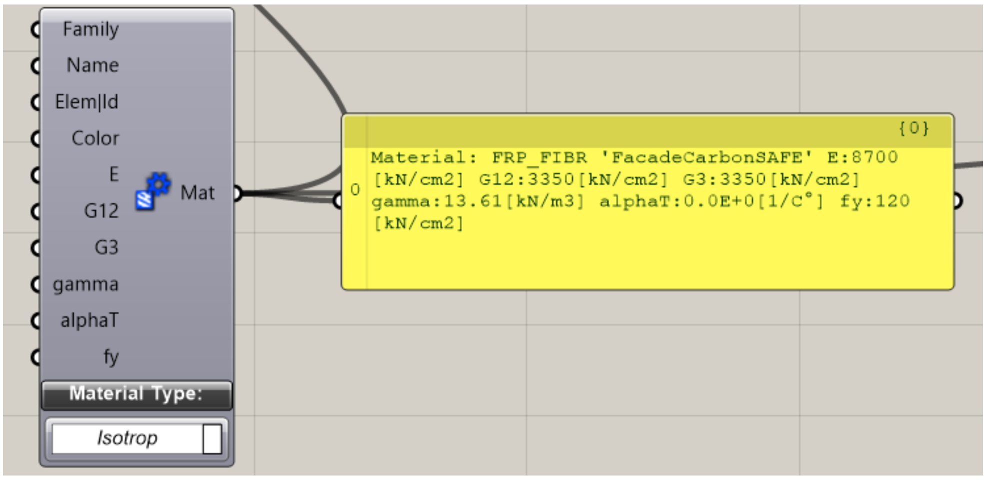


Figure 42: Defining the CFRP properties in Karamba

A list of options must be introduced in Karamba to perform the optimization of the cross-sections, Figure 43. Contrarily to regular steel structures, in which different sizes of the for the same cross-sections are available, in wound CFRP structures the cross-sections are the result of the number of rovings that form each member. To represent this, a list of areas referring to the number of rovings in each cross section was created by taking the diameter of 1x50K roving (d = 2.4749 mm) and multiplying it by the number of rovings (1,2,3,…), i.e. each cross-section was defined by the number of diameters it assembled.

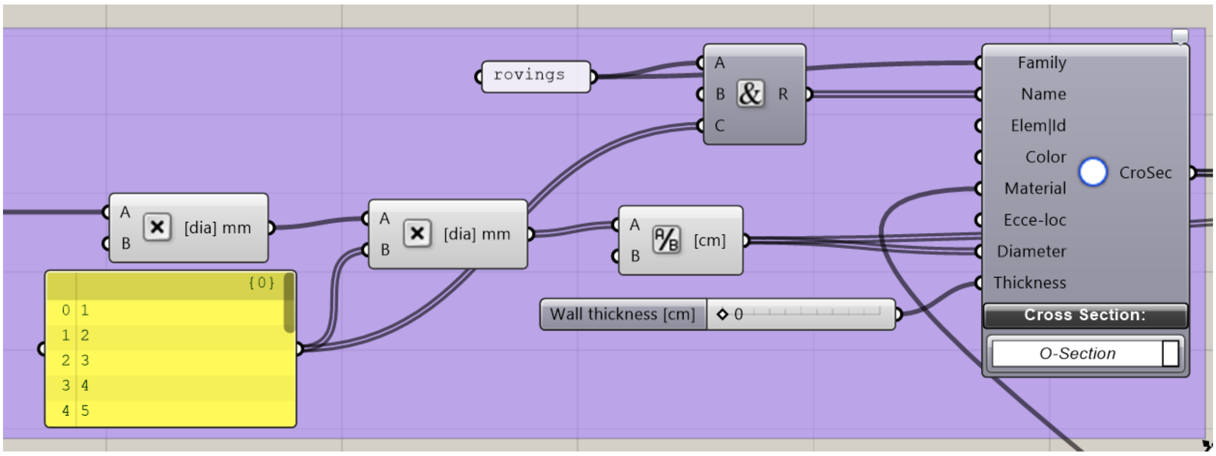


Figure 43: List of cross-sections is added according to the number of rovings that compose each cross-section

For the supports, the same constraints used in Peregrine were assumed: all rotations and translation movements were restrained.

Finally, when defining the loading, a more accurate and detailed setup was necessary to implement the cross-section optimisation – as the amount of material in each element is directly proportional to the magnitude of force it needs to carry.

Given the site location for the canopy and its surrounding environment, the loads considered were snow, wind, dead-load (from the roof panels) and self-weight (of the carbon fibre structure). In accordance with EN 1990 – Eurocode: Basis of structural design [25] regarding the limit states ULS (ultimate limit state) and SLS (serviceability limit state) the corresponding load combinations were defined. For ULS the fundamental combination was applied:

$$\mathrm{E_d} = \sum_{\mathrm{j}\geq 1} \gamma_{\mathrm{G,j}} \mathrm{G_{k,j}} \text{"} + \text{"} \gamma_{\mathrm{Q,1}} \mathrm{Q_{k,1}} \text{"} + \text{"} \sum_{\mathrm{i}>1} \gamma_{\mathrm{Q,i}} \Psi_{0,\mathrm{i}} \mathrm{Q_{k,i}} \tag{5}$$

For SLS the characteristic combination was applied:

$$E_d = \sum_{j\geq 1} G_{k,j} \text{"} + \text{"} Q_{k,1} \text{"} + \text{"} \sum_{i>1} \Psi_{0,i} Q_{k,i} \tag{6}$$

Given the material properties of CFRP, Karamba is able to automatically calculate the self-weight of the carbon fibre structure. For the roof panel, polycarbonate sheets of (2 x 1 x 0.012) m were considered. To calculate both the action of wind and snow the procedures in Eurocode 1 (EN 1991) combined with the UK National Annex [27] were followed.

In the wind calculations, the basis for monopitch roofs according to 'Eurocode 1: Actions on structures - Part 1-4: General actions - Wind actions' [26] were considered. The following (Table 1) summarizes the parameters involved in the evaluation of the wind loads:

Table 1: Parameters involved in the evaluation of the wind loads

Description	Variables	Values
Terrain category		III
Basic wind velocity	v_b	0.20 m/s
Height above ground	h	3.00 m
Roof Angle	α	1º
Degree of Blockage under Canopy	φ	1
Orography factor	$c_o(z)$	1
Air density	r	1.25 kg/m^3
Roughness length	z_0	0.30 m
Minimum height	z_{min}	5.00 m
Terrain factor	k_r	0.215
Mean wind velocity	$v_m(z)$	13.33 m/s
Turbulence intensity	$I_v(z)$	0.36
Turbulence factor	k_I	1.0
Peak velocity pressure	$q_p(z)$	0.39 kN/m^2

As a result, values for uplift wind and downwind acting on the structure were calculated. Confirming the assumption made at the beginning, uplift wind had a more relevant impact on the structure than downwind. For uplift wind, the result was 0.511kN/m² and for downwind the result was 0.093 kN/m², both loads are assumed to be applied uniformly to the roof panel.

For the snow action, the 'Eurocode 1: Actions on structures - Part 1-3: General actions - Snow loads' [28] was used, considering the canopy as a roof abutting to taller construction works, Figure 44 (section 5.3.6 of the Eurocode).

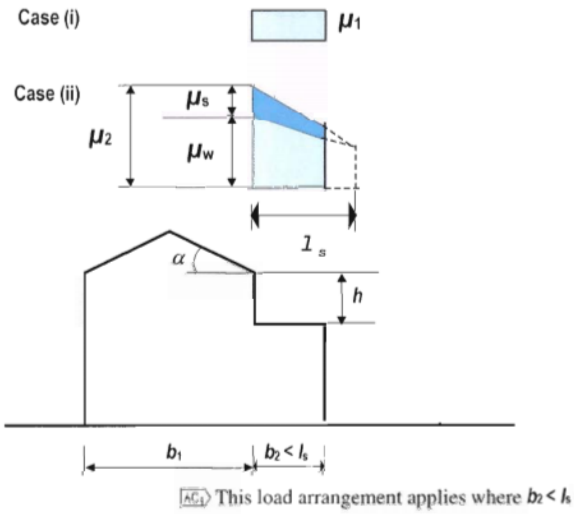


Figure 44: Figure 5.7 from EC1-1-3 [28]

In Table 2 are summarized the parameters involved in determining the snow loads acting on the canopy.

Table 2: Parameters involved in determining the snow loads acting on the canopy

Description	Variables	Values
Length of snow drift or snow loaded area [m]	l_s	10
characteristic value of Snow load on the ground [kN/m2]	S_k	0.282
Height of construction work [m]	h	5
Width of construction work [m]	b_1	8.5
Width of construction work [m]	b_2	2

snow load shape coefficient (case(i))	μ_1	0.8
snow load shape coefficient (case (ii))	μ_2	1.1
snow load shape coefficient due to sliding of snow from the upper roof	μ_s	0
snow load shape coefficient due to wind	μ_w	1.05
Snow load on the roof (case(i)) [kN/m2]	S1	0.226
Snow load on the roof (case(ii)) [kN/m2]	S_2	0.296

Due to the uncertainty in some of the information regarding the geometry of the surrounding buildings, some assumptions had to be made. The final result considered for snow acting on the structure was a load of 0.296 kN/m^2.

The loads were applied as point loads in the positions of the connections between the roof panel and the carbon fibre structure, according to the influence area of each connection. The combinations corresponding to the worst cases in SLS and ULS were combination number 3 and number 8, respectively. For SLS, combination 3 included dead load (DL), super-dead load (SDL) and snow (S1) acting on the structure. For ULS, combination number 8 with DL and SDL as permanent actions and S1 and downwind (W2) as variable actions – S1 was the leading and W2 was the accompanying action. In the following image, there are listed the combinations considered according to the partial safety factor they adopt for each SLS and ULS combination. From 0 to 3 are the SLS combinations and from 4 to 8 are the ULS combinations, Figure 45. These factors are multiplied by the respective actions later in the script.

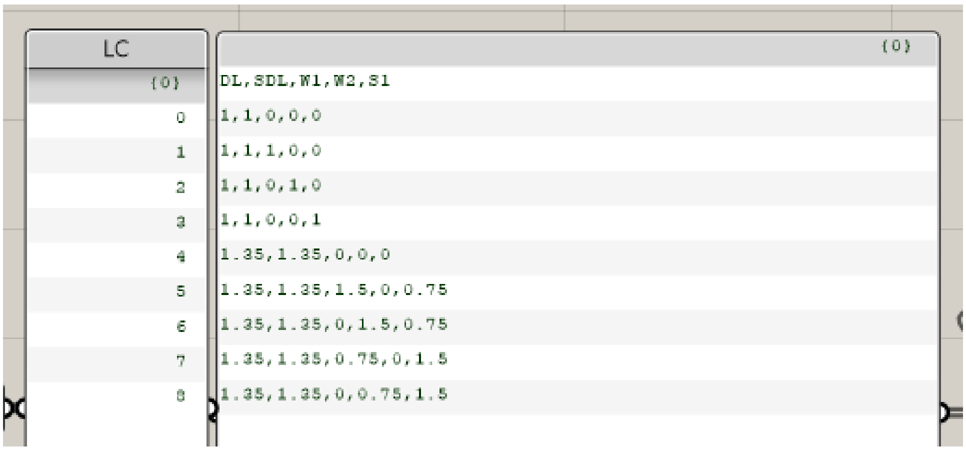


Figure 45: Defining the load combinations in Karamba, each line is filed with the coefficients that affect each load, according to the combinations considered

Once all these aspects were defined, Karamba was ready to generate the models. In this phase, the optimisation had not occurred yet. Karamba assumed the cross-section of the structure as the first one on the list, in this case a cross-section of 1x50K roving. This first model is connected to 'Analyze', Figure 46, the component responsible for running the first order analysis according to the theory of small displacements.

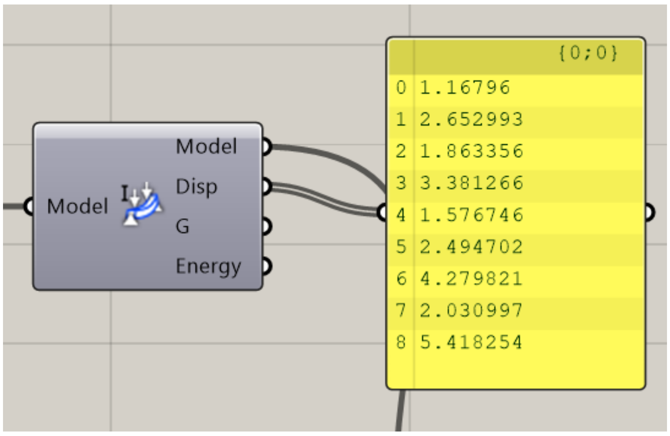


Figure 46: 'Analyse' component in Karamba, showing the maximum displacement resulting from each combination

One of the outputs of this component is the maximum displacement within the structure for each load case (this result is in centimetres). For the worst SLS combination (number 3), the maximum displacement was of 3.4 cm. For a cantilever, the typical vertical defection limit is given by span/180 [29]. In this case the limit would be 1.1 cm. Before the cross-section optimisation was implemented, the script automatically adopted the first element in the list of cross-sections – in this case a section composed of one roving – so it was expected that the resulting displacement would be bigger than intended. This indicated the need to perform a cross-section optimisation, allowing the script to increase the cross-sectional area for each element as required. For this, the component 'OptiCroSec' was added, Figure 47.

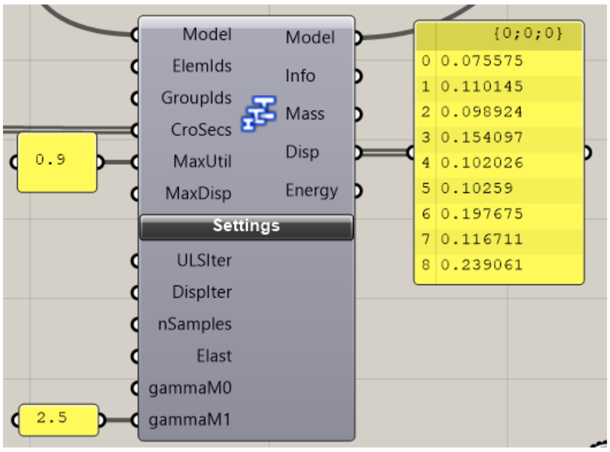


Figure 47: 'OptiCroSec' component in Karamba

To perform the optimisation, this component was fed with the previously analysed model and the cross-section list. It was also needed to add a limit for the maximum utilisation of the cross-sections (adopting a conservative approach, it was set at 90%) and finally, depending on whether it was necessary or not for each model, a material safety factor ('gammaM1'). This factor was added in order to prevent the occurrence of global buckling. The optimisation algorithm for cross-sections also checks each element for local buckling, based on the buckling length of each member. Unlike Peregrine, Karamba is able to consider both global and local buckling in the cross-section optimisation.

To check for global buckling the 'Buckling Modes' component is added. First a second order analysis is carried through 'AnalyzeThII' component which determines the normal N^{II} forces that result in second order effects. This information is passed onto the 'Buckling Modes' component which computes the buckling modes as a result. The 'BLFacs' outputs a list of the buckling factors corresponding to each buckling mode for every load combination. Figure 48 shows the snippet of the script that involves both of the referred components.

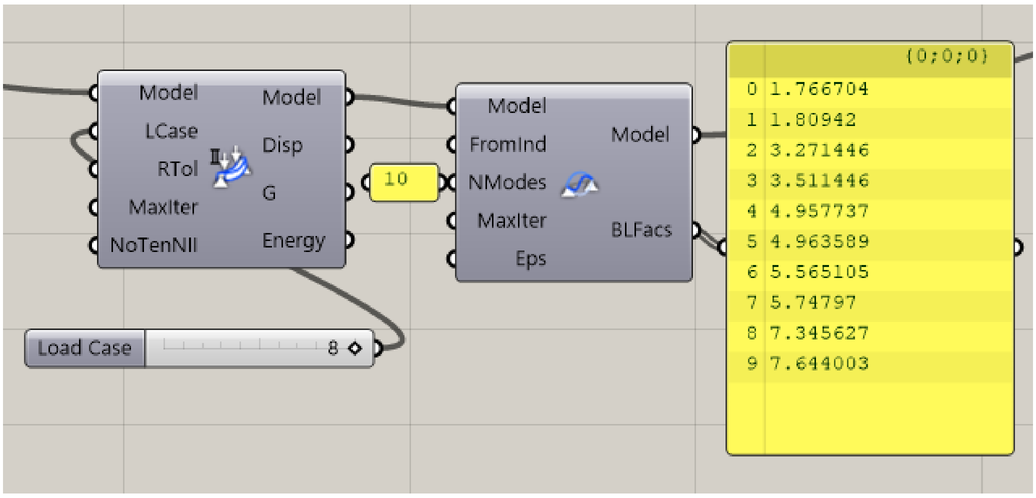


Figure 48: ‘AnalyzeThII’ and ‘BLFacs’ components in Karamba

The goal of optimising the cross-sections was to reduce the deflection while also optimising the amount of material used. In order to measure the amount of material required for each model a script was created – knowing the length of each element and the number of rovings that composed each cross section it was possible to calculate the amount of meters of CFRP roving that would be spent, Figure 49. As previously mentioned, there was also an interest in reducing complexity, so it was also important to know the number of different cross-sections each model required – to calculate this a simple C# script was added, Figure 50.

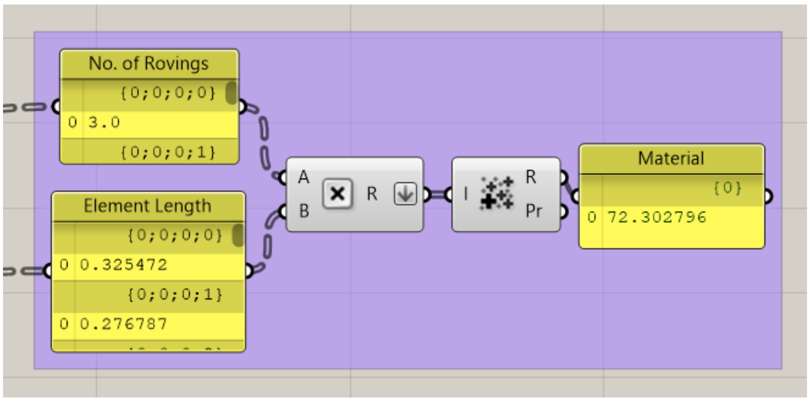


Figure 49: Snippet of the script that determines the amount of material required, in meters

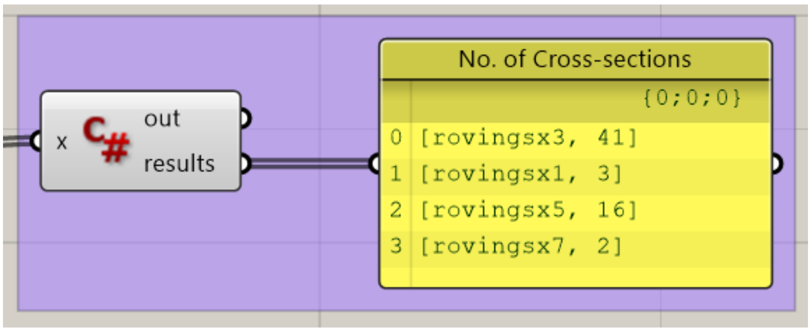


Figure 50: Script created to determine the number of cross-sections that compose the structure

3.2.5. Results and comparison

After analysing each model using both Peregrine and Karamba3D, it became possible to compare all the possible solutions in order to choose the best one. Ultimately, the best option would be the one which combined economy, both in material and cost wise, with simplicity in terms of its geometry.

The complexity of each geometry can be demonstrated through the number of bars and nodes within a structure. Additionally, another good indicator is the number of different cross-sections – in this case the complexity would come in the construction phase, as usually it is preferred to have a limited number of different cross-sections throughout the whole structure.

In terms of material quantities, the information was obtained from Karamba. A summary of the characteristics of each option can be found in Annex 3. To compare all of the options available, three main parameters (Annex 3) were selected: number of bars, number of nodes and amount of material spent. By analysing these parameters, the best options were the ones resulting from A6B5 with 4 connections, Figure 51, and with 6 connections, Figure 52, (refer to the geometry matrix in section 3.2.2). The rendered versions of every option can be found in Annex 4.

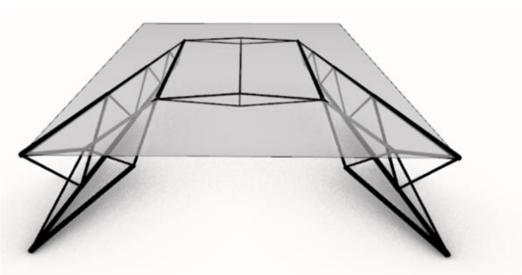


Figure 51: Rendered model A6B5 with 4 connections

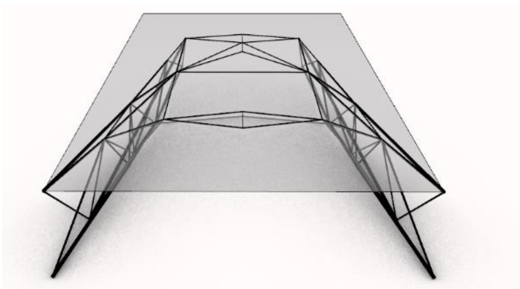


Figure 52: Rendered model A6B5 with 6 connections

In order to choose the best structure, it was still necessary to understand the behaviour of the roof panel and how the number of connections would influence it.

3.3. Roof panel

Initially three different kinds of materials were considered as potential choices for the roof panels: glass panels, acrylic sheets, and polycarbonate sheets. Cost wise glass panels were more expensive and more fragile to work with. As a result, this option ended up being discarded early on. The other two options were very similar both in price and in their mechanical properties (density, tensile strength, elastic modulus). However, there was one detail that distinguished them: their failure behaviour.

Polycarbonate sheets have a ductile failure behaviour while acrylic sheets are brittle. Generally, in designing structures, the choice for materials tends to lean towards ductile materials. The reason for this is because they show signs of eminent failure before it occurs – giving enough time for measures to be adopted in order to prevent failure. For this reason, the final choice for the roof panels material was polycarbonate.

A model of the roof panel was generated – considering 4 support points (simulating the connections with the CFRP structure). In this way, it was possible to understand the changes in stress – if the roof panel could support the stress with only four fixings, then this would clearly be the best option, if not some changes would have to be considered and studied (e.g.: increasing the thickness of the roof panel - this would increase the dead load in the canopy which could lead to more roving being spent). Ultimately it could be a better option to increase the number of fixings to 6.

The model was composed by a rectangle of (1 x 2) m, and 0.012 m of thickness. The following properties were used to model a polycarbonate sheet: specific weight (12 kN/m^3), elastic modulus (2.1 GPa), yield strength (56 MPa) and Poisson's ratio (0.37) [10]. For the loadings, uplift wind (0.511 kN/m^2), down wind (0.093 kN/m^2) and snow (0.296 kN/m^2) were considered as well as the panel's self-weight (automatically calculated).

To analyse the roof panel behaviour under the different load combinations regarding ULS (fundamental combination) and SLS (characteristic combination), according to Eurocode 0 [25] the following were defined (as it was previously described for the carbon fibre models), Figure 53:

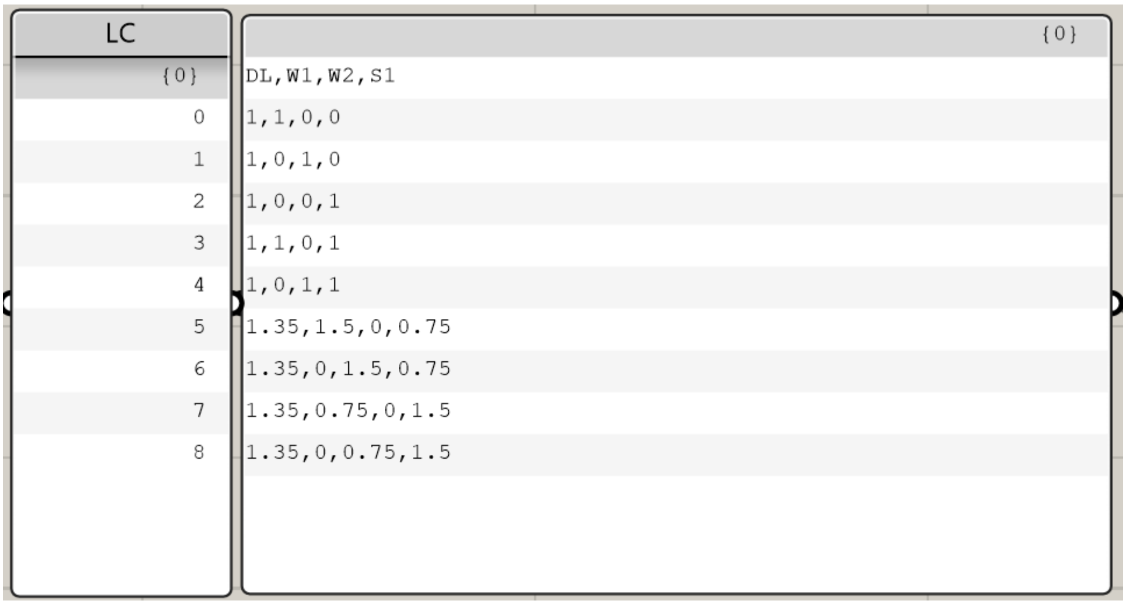


Figure 53: List of coefficients that affect each load acting on the panel, according to the considered combinations

In this scenario, DL was the self-weight of the roof panel and SDL was discarded. Again, the worst SLS combination was the one combining the weight of the roof panel with downwind and snow. Likewise, for ULS, the worst combination involves snow load as the leading action and downwind as the accompanying action.

In Karamba3D, the models were generated considering the rectangle as a shell surface which was then discretized through the application of meshes.

Similarly to the other models in Karamba, the panel model went through a first order analysis, and the output showed the maximum displacements for the SLS load combinations, Figure 54. The worst combination resulted in a maximum displacement of 1.24 cm on the edges. Considering this is a lightweight structure and the only consequence of the deflection is merely an aesthetic aspect, this result was considered to be sufficient.

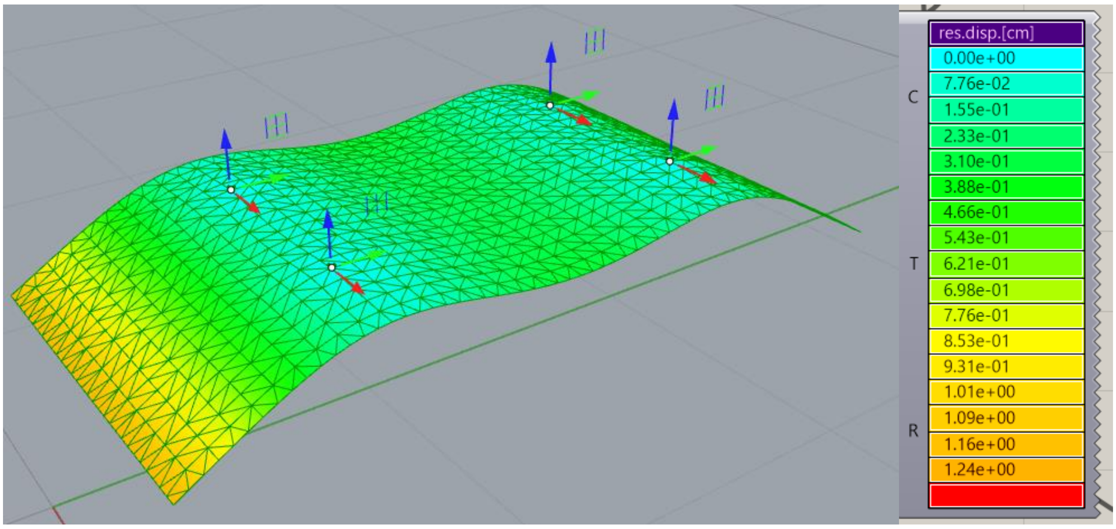


Figure 54: Displacement distribution in the roof panel under the action of the worst SLS combination

Regarding the stresses and the behaviour of the panel, Karamba uses the Von Mises stresses and the yield strength to calculate the utilization in the roof panel, Figure 55, as the ratio between yield stress of the material and the maximum Von Mises stress along the panel's cross-section hight.

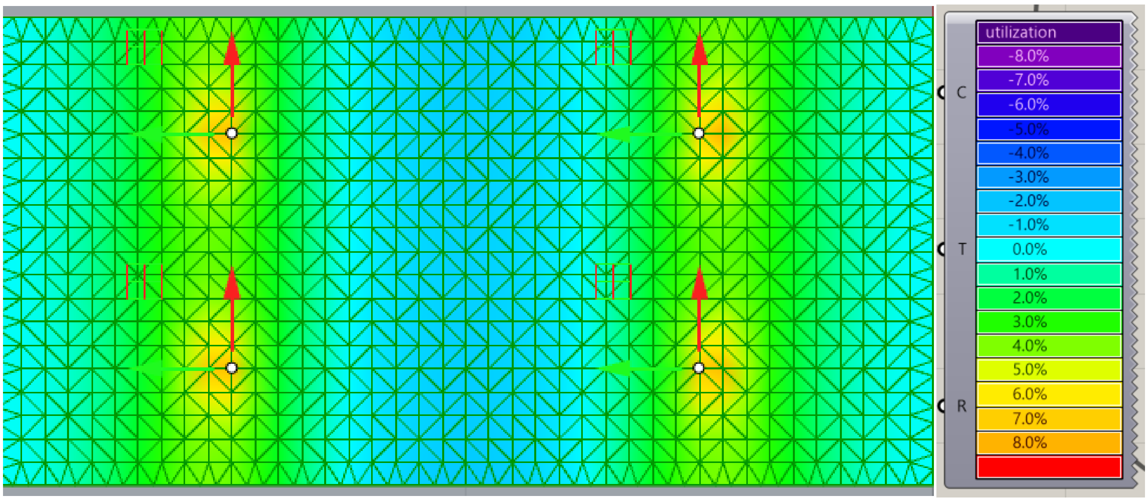


Figure 55: Stress utilization distribution in the roof panel for the worst ULS combination

The results show that for the worst load combination there are peaks of stress surrounding the positions of the fixings. Nevertheless, the roof panel's behaviour satisfies the design criteria as the maximum utilisation is of 8%.

In conclusion, the model with 4 fixings can be considered as the best choice among all the options considered.

3.4. Connection design

The design of the connections to the wall was done using the Hilti PROFIS Engineering software. This software uses ETAG (European Technical Guidelines) in the design of masonry fixings – ETAG 029 Annex C [30].

According to Annex C of ETAG 029, the design resistance is calculated as follows:

$$Rd = Rk/\gamma M \tag{7}$$

In which, R_k characteristic resistance of a single anchor or an anchor group and γ_M is the partial safety factor for material.

There are two methods of design for ULS described in this document, the software follows the general design method A.

The loads acting on the connection are obtained from the Karamba model – reactions on the supports for the worst ULS combination (combination 8).

Figure 56 shows the list of the reaction forces, coordinate position and reaction moments of each support, respectively. The reaction forces in x and z correspond to shear (V_x and V_z) acting on the anchor and the force in y represents the axial component (N) acting on the anchor. One detail worth mentioning is the magnitude of the bending moment values – they are residual – this was to be expected as in optimising the structure, it tends to work mainly in tension and compression reducing the bending moments (as already mentioned in Chapter 2).

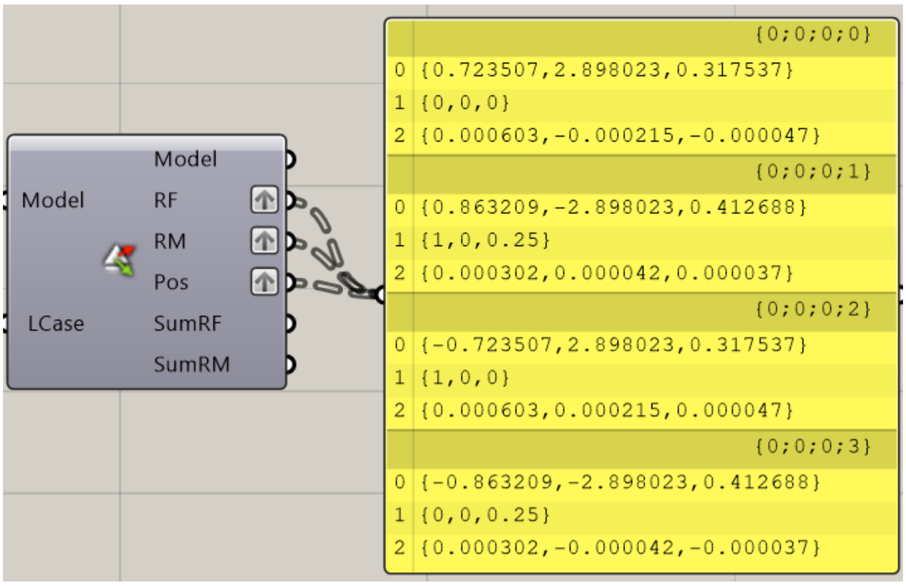


Figure 56: Reaction forces on the wall

The software runs the analysis for tension and compression separately and verifies the behaviour of the anchorage for failure of the metal part, brick edge failure, local brick failure, pushing out of one brick (for shear), and failure of the metal part, brick breakout failure, bond and pull out of one brick (for tension). Then it runs the analysis for the combined actions of shear and tension.

The anchorage design, in which the resistance is calculated considering the combined actions of shear and tension loads, must satisfy the following equations:

$$\beta_N \leq 1{,}0 \tag{8}$$

$$\beta_V \leq 1{,}0 \tag{9}$$

$$\beta_N + \beta_V \leq 1{,}2 \text{ for solid masonry} \tag{10}$$

$$\beta_N + \beta_V \leq 1{,}0 \text{ for perforated or hollow masonry} \tag{11}$$

With β_N and β_V as the ration between design action and design resistance (for tension and shear respectively).

Annex 5 provides the reports generated in the design of these connections. These include information regarding the material of the wall, the geometry of the baseplate and the anchor type considered, load cases and the verifications considered.

4
FABRICATION

4.1. Overview

Since the conception stage of this project there has been an inherently co-dependent relationship between geometry, material, and fabrication. As previously mentioned, this research was influenced by the ITKE/ICD Research Pavilions, resulting in the choice of CFRP rovings as the material for the loadbearing structure of the canopy. Given its anisotropic behaviour and in order to take advantage of the strongest orientation of the fibres, the structure was designed assuming a unidirectional behaviour of the fibres – thus the choice of Peregrine for generating a geometry. Accordingly, a choice of fabrication that followed the same philosophy was made.

The approaches adopted in fabrication are controlled by the geometry and the cross-section properties of the FRP element being produced. Most processes require the use of some sort of formwork for shaping the components. One example of these well-known methods is called pultrusion – usually used in the production of sections and sheets [10]. This method consists of pulling rovings embedded in resin through a heated mould where the polymer will be cured at high temperatures (the rovings can also be dry and the resin added later into the mould). Many other processes are available depending on the characteristics intended for the FRP component. The ones that count with the use of moulds usually forgo the ability to have precise control over the position of the filaments, which is not favourable in the context of the canopy structure.

In its traditional implementation, filament winding is a fabrication process that consists of pretensioning rovings (wet, or dry and later combined with the resin) winding them around a rotational mandrel, Figure 57. The production of the mould involves an elaborate process and wasting of material, as usually these moulds are not reused. This technique is often applied in the fabrication of pipes, vessels, tanks, and other rotationally symmetrical hollow components [10], Figure 58. Although this process also involves the use of a mould – the mandrel – there is a variation of this technique called coreless filament winding (CFW). As the name suggests, this variation was conceived with the intent of reducing the need for formwork. [31] The method chosen for the construction of the canopy is based on this process.

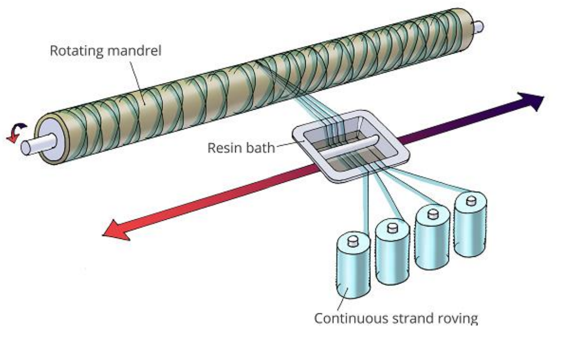


Figure 57: Classic Filament Windind scheme. Adapted from https://aliancys.com/en/products/processing/filament-winding/ *accessed in 13/06/2020*

Figure 58: Typical products from the classical filament winding technique

4.2. CORELESS FILAMENT WINDING

Coreless filament winding is a process that has been studied and developed by the Institute of Building Structures and Structural Design (ITKE) and the Institute for Computational Design (ICD) at the University of Stuttgart. This method has been applied to the construction of the ITKE/ICD Research Pavilions (2013-14 and 2016-17) and of the Elytra Filament Pavilion (Figures 59, 60 and 61). Thus, these structures were used as a benchmark to understand how to adapt this method in the construction of the canopy.

Figure 59: ITKE/ICD Research Pavilion 2013-14 made through the application of CFW [6]

Figure 60: ITKE/ICD Research Pavilion 2016-17 made through the application of CFW [5]

Figure 61: The Elytra Filament Pavilion also made with the application of CFW, displayed at the Victoria and Albert Museum, London, UK

Unlike classic filament winding, coreless filament winding is a process that does not require the use of a positive mould. Instead, it replaces the traditional mandrel with a spatial framework that provides the necessary scaffolding for the winding of the resin-soaked fibres [32]. While minimizing the amount of formwork being used, this method allows for a large degree of freedom in the geometry and layout of the rovings within the CFRP component [31]. Furthermore, by not requiring the use of individual moulds, this method reduces the waste of material and saves resources that would be implemented in creating these moulds – resulting in a more efficient method [31].

As a substitute for the mandrel, a linear frame (usually made of steel) is used as temporary scaffolding to hold the resin-soaked rovings in place during the winding process. This frame is the discretization of the continuous mould (mandrel) in a bunch of anchor points located within the spatial framework [32]. This framework also provides a stable base capable of withstand the tension forces that develop during the winding [33].

The control points are connected through the continuous winding of fibres in a particular sequence. The final result is a structure geometrically defined by the sequential winding according to the major stress orientations in order to increase material efficiency and structural performance [33]. Thus, the precision in the position and orientation of each roving acquires a greater degree of importance as it is closely linked with structural performance.

The sequence in which the fibres are wound, the precision needed in positioning the control points and the potentially large number of these points to be wrapped efficiently prompted the development of robotic fabrication processes.

The method developed for the construction of the pavilions, even though it suffered some adaptations according to the needs of each structure, usually included the use of two synchronized industrial robots for the winding process. One robot is designated as the master and the other as the slave. The two are programmed to perform the winding in synchrony generating the intended geometry, Figure 62 [31]. In these pavilions, the materials were glass fibre rovings and carbon fibre rovings. First, the glass fibres were pre-impregnated with resin by going through the stationary resin bath and were the first to be wound acting as a deformable scaffolding for the later added carbon fibre rovings [33].

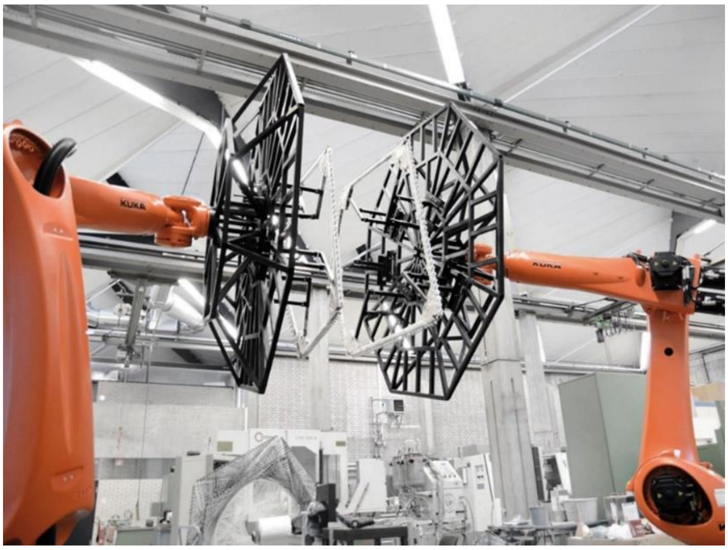


Figure 62: Robotic arms with the metal effectors attached ready to start the winding process:

In order to maintain the precision in the winding process, it is crucial that the relative positions of every element of the fabrication process is properly defined so that the digital model used for simulation matches the physical setup [33]. This includes the position of both robots, the spaceframes, and the resin bath.

Finally, after the winding and curing of the polymer, the scaffolding is ready to be removed. This method was first applied in the construction of large scale monocoque structures [31], and later to smaller individual components which serve as the basic components of modular structures [32]. Thus, it seemed suitable for the construction of the canopy.

4.3. Canopy fabrication

Contrary to the usual structures that have been created through coreless filament winding, the canopy has a truss-like geometry. It is fundamentally composed of nodes and links, so any change in the position of nodes or the orientation of fibres will have a major impact on the behaviour of the structure.

The construction of the canopy is based on the concept of coreless filament winding in the sense that it also employs a spatial framework to define the position of anchor points. However, instead of resorting to robotic fabrication processes, the winding is done manually. The reason for this decision was that as a spaceframe structure, the density of fibres was much lower than that of previous CFW made structures, significantly reducing the complexity of construction. Regardless, the sequence of the winding maintains its importance.

In order to simulate the fabrication process of the canopy, a scaled model was built. The model is scaled at 1:4. It is based on the resulting structure for A6B5 with 4 connections to the roof panel. It was built using a cardboard panel that emulates the roof panel and the wall (i.e. the surfaces that include any sort of fixing) and strings representing the CFRP rovings.

The real fabrication process starts with the roving going through the resin bath and then being tied to the starting node. This node will define the starting point of the winding sequence. From here the resin-soaked roving will be continuously wound through the nodes - defined by the scaffolding - creating the canopy's geometry until it reaches the final node. There the roving will be tied with a knot, as it was done with the starting node. In the simulation of the process the resin bath stage will not be included as it has no impact on the sequence of winding.

To create the scaffolding, fine timber sticks were inserted into the cardboard panel in a way that at the tip of each stick (top or bottom) was the exact location at which the wrapping of the fibres should occur. The geometry of the canopy is consistent with that of a space frame, therefore, the precision regarding the position of each node should be prioritized given the influence it can have in the behaviour of the structure. Accordingly, special attention to the setting up of the scaffold is required.

The definition of a winding sequence was a process of trial and error. However, to facilitate this an adjustment was made to the Karamba3D model of the structure. When defining the cross-section list, the diameter of 1x50k rovings was multiplied by a list of numbers resulting in a sequence of one roving, two rovings, three rovings, etc. If the list only has odd numbers or only even numbers, it is possible to predict the direction at which the rovings should be wound. In other words, if a list is created with even numbers, the fibres always end up returning to the initial anchor point (Figure 63), but if they are odd numbers, they always finish in the other node (Figure 64).

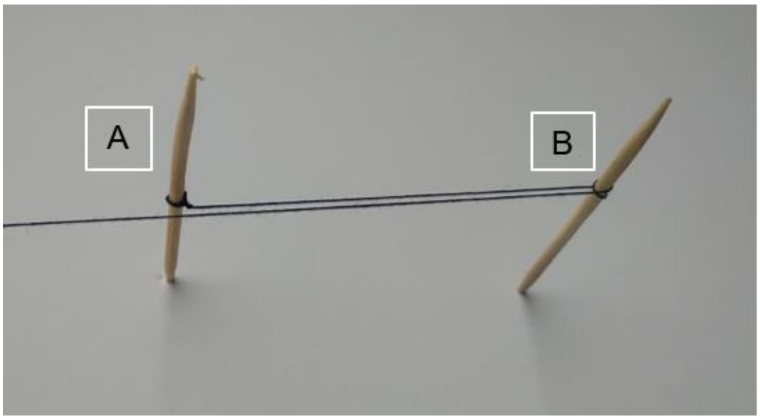


Figure 63: Cross- sections from a list of even numbers - cross-section with 2 rovings has a A-B-A sequence

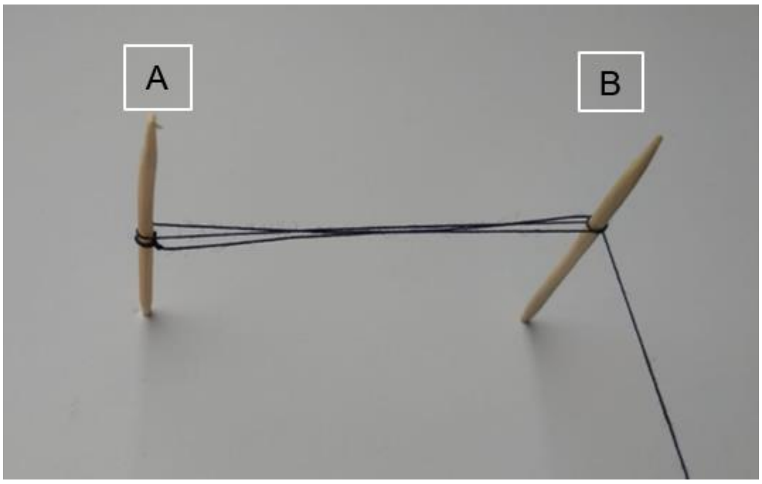


Figure 64: Cross- sections from a list of odd numbers - cross-section with 3 rovings has a A-B-A-B sequence

For this model, the list of cross-sections made of odd numbers was adopted, this way the winding direction kept moving forward. The completed model is shown in Figure 65, along with detailed images of the scaffolding (Figure 66) and the node winding details (Figure 67).

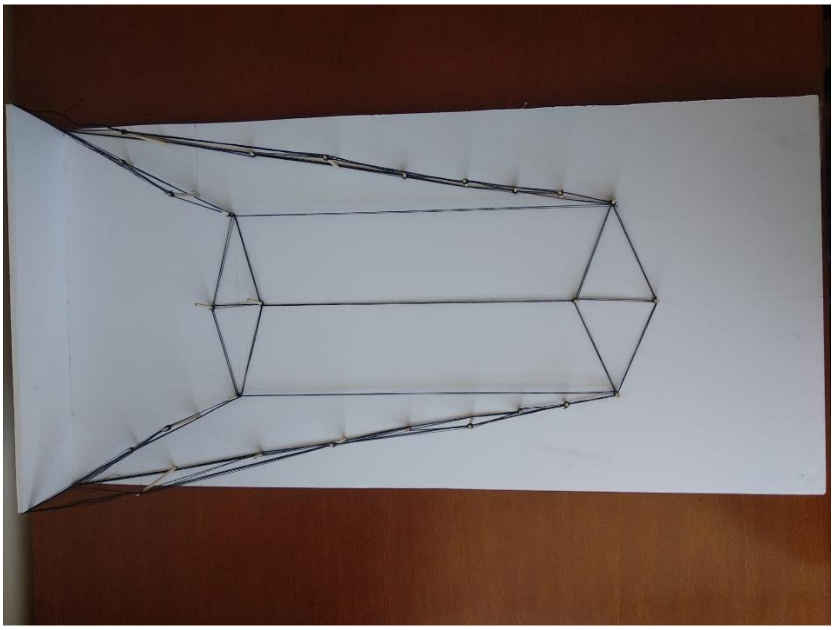


Figure 65: Scaled model (bottom view)

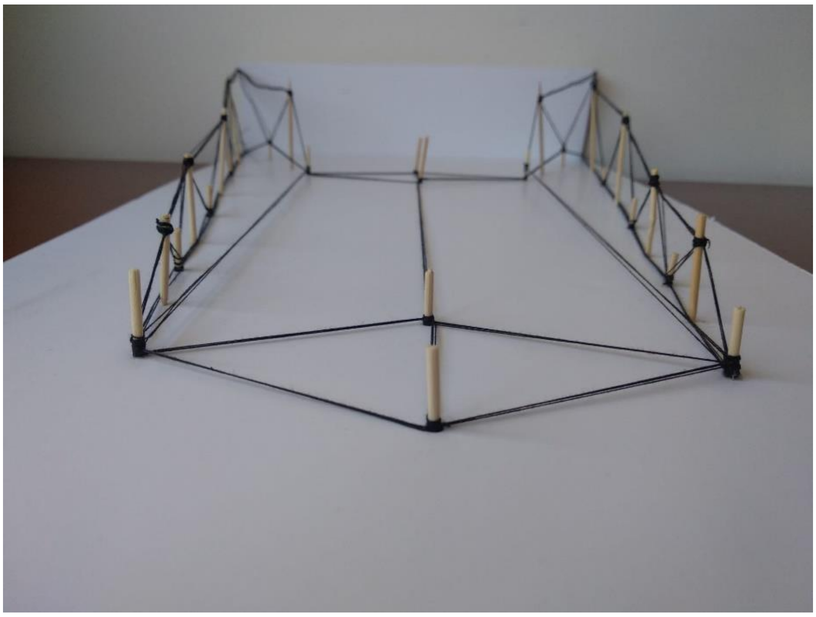


Figure 66: Scaffolding using wooden sticks

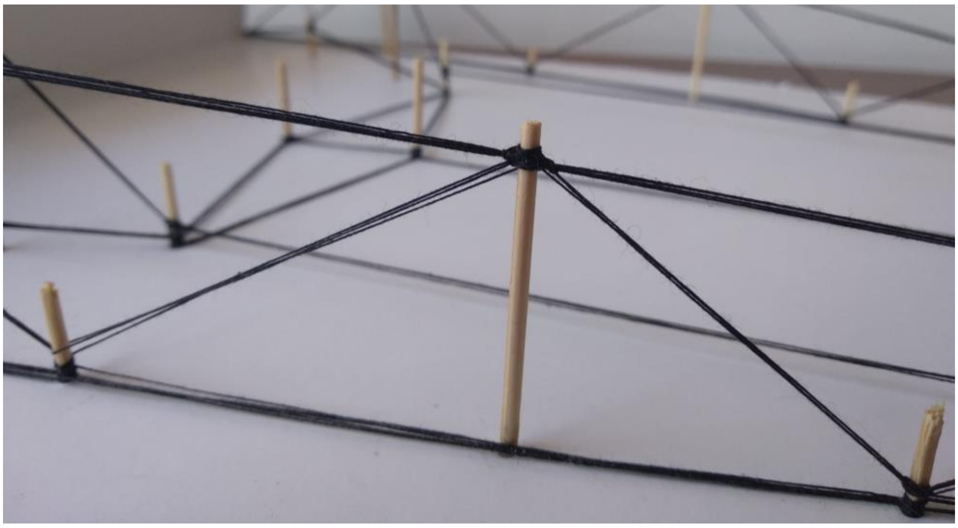


Figure 67: Node detail

4.4. CONNECTION DETAIL

Following the same approach used in the reference projects for this canopy – the ITKE/ICD Research Pavilions – in which aluminium sleeves were included in the winding frame so that the fibres were wound around them, and as the epoxy resin cured they became a permanent part of the structure [31]. These sleeves marked specific locations that allowed the linkage of components using steel bolts that creating connections between the modules of the structure or other components [31].

The same approach was adopted for the conception of connections between the canopy CFRP structure and the roof panels. Two types of connections were conceived. The first type was the one corresponding to the connections that carry the forces being applied in the roof panel to the structure - they have a structural role, Figure 68. Their position was planned and included in the model. In the sketch of the detailing of this type of connection, it shows the bolt going through the roof panel, leaving enough thread length (about 10 mm) for the winding of the fibres. This length is covered by the aluminium sleeves - providing a less rough surface for the winding – and then secured with a washer and nut.

The second type of connection, Figure 69, appeared after the generation of geometries and has a mere constructive role in the canopy. These connections hold the fibres in the right position without carrying load from the roof panel to the structure. The detailing sketch of the connection shows that the bolt going through the panel and being secured by groups of washers and a nut at the bottom. The threaded length should be adapted to the requirements of node, in order to maintain the geometry of the structure.

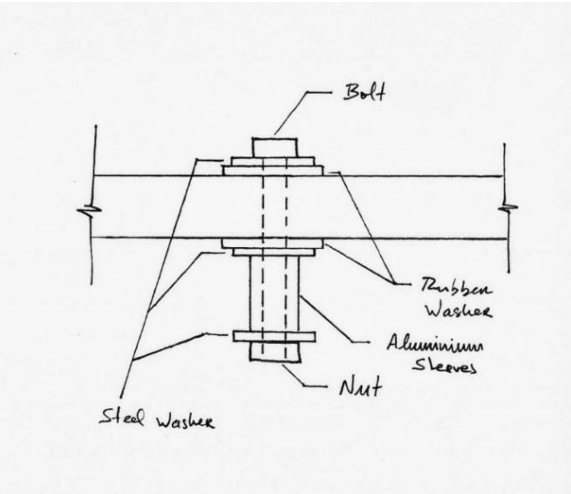


Figure 68: Connection of type 1

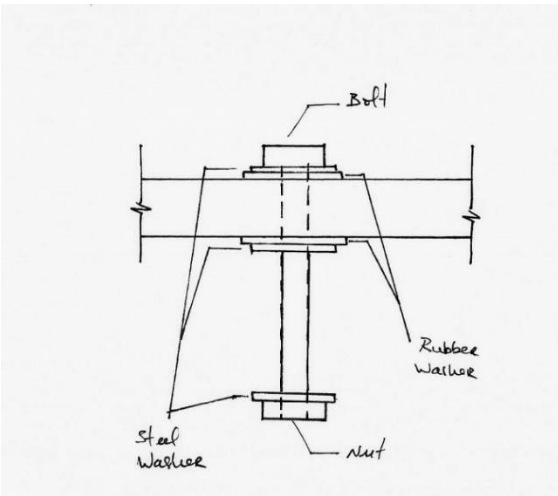


Figure 69: Connection of type 2

5
FINAL RESULTS AND CONCLUSIONS

5.1. RESULTS

The product of this study was the design of the carbon fibre canopy. Which includes the conception of a geometry, the connections to the wall and the fixings between the roof panel and the CFRP structure. This section assembles the information regarding the design of the final structure.

The optimal solution in terms of material usage and complexity of geometry was the geometry resulting from the A6B5 domain (refer to section 3.2.2 for the complete geometry matrix), Figures 70 and 71.

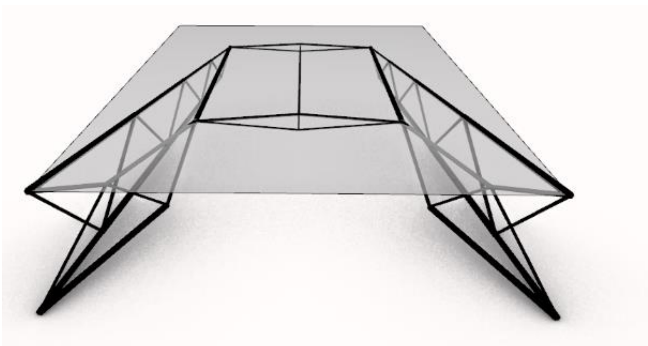


Figure 70: Perspective view of A6B5 geometry with 4 connections

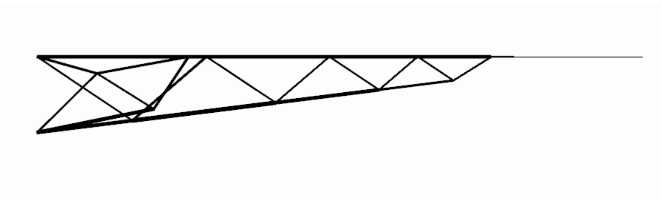


Figure 71: Side view of A6B5 geometry with 4 connections

After being adapted to the fabrication process with new cross-sections, each module of the canopy's CFRP structure uses 72.3 m of carbon fibre rovings. Overall, it has four different cross-sections. It weighs 2.07 kg and it was designed to withstand around 112 kg of extra load (besides the weight of the roof panel and the structure itself).

A final representation of a module of the canopy in the construction site was made (Figure 72) using Fologram – a plugin for Rhino and Grasshopper that allows the application of augmented reality using the 3D models created using this software.

Figure 72: Using augmented reality to see the final geometry for one module of the canopy

With regard to the connections, they are divided into roof panel/CFRP structure, and wall/CFRP structure. The first group has two types of connections: the four connections that are responsible for transmitting the force between the roof panel to the CFRP structure and the connections that are responsible for holding the fibres in place.

The connections to the wall were conceived using the HILTI software. Each of these connections requires a steel plate that is connected to the wall through four anchorages ( ). Attached to this plate is also the connection that holds the fibres.

Lastly, a map of quantities for the material used in the construction of each module of the canopy is presented in Table 3

Table 3: Map of quantities for the construction of one module of the canopy

Material	Quantity
Epoxy resin [l]	(1)
Carbon fibre roving [m]	73
Steel Plate (100 x 100 x 10) [mm]	4 units
Anchorages	16 units
Bolts (M5)	16 units
Metal Washers	48 units
Aluminium sleeves	4 units
Rubber washers	32 units
Nut	4 units

(1) This value depends on the volume of fibres used. Usually the volume ratio is 40% fibres and 60% epoxy resin

5.2. CONCLUDING REMARKS

This dissertation presented the development of a workflow suitable for the optimisation of CFRP structures. This premise was validated with the conception and design of the carbon fibre canopy.

From reviewing several optimisation approaches, it became clear that there is no best optimisation process, each of them has its own advantages and disadvantages. It is the engineer's job to be able to choose the one that best fits the context of the problem.

In the context of this research, the goal was to find the right method for creating a frame structure, while using CFRP rovings. Given the unidirectional nature of CFRP rovings with its high strength, the final choice was layout optimisation applied through the implementation of Peregrine.

Regarding the use of Peregrine, some of its limitations shaped some approaches in the workflow, namely the non-inclusion of buckling behaviour in the optimisation process, and the difficulty in modelling plate surfaces (that lead to the inclusion of imposed connections in the roof panel).

The final structure is the result of a combination of optimisation processes starting with layout optimisation followed by a cross-section optimisation according to the specificities of the material. This resulted in a structure optimised according to material usage, and with a acceptable degree of complexity to be built.

From this research, it is possible to conclude about the high potential of using composite materials in structural application. Their high strength-to-weight ratio allows great savings of weight while maintaining the strength – this is a favourable aspect for the design of lightweight structures. The flexibility in adapting to create complex and even eccentric geometries, opens the opportunity for engineers and architects to be bolder in the conception of new structures.

Nevertheless, at this stage the selection of CFRP composites as the base material for a structure is still only being explored and considered in an academical context, with some rare exceptions occurring in the engineering practice. This situation is due to the cost of production being high and thus not a viable option in many situations. Also, the fabrication processes are not developed enough to be applied in current construction practice.

5.3. FUTURE WORK

During the development of this project some aspects that could be explored in the future were identified.

In the generation of geometries, the process adopted was layout optimisation because it allowed the explicit application of the unidirectional trait of CFRP rovings in discrete elements - in a truss-like structure. It would be interesting to also explore the more traditional topology optimisation methods that result in a continuum domain of material. In this way it would be possible to study the interaction between fibres and study new challenges that could arise.

Another discussed aspect was the possibility of designing the wall-connections. The connections would be tailored to the need of the canopy and later 3D-printed, providing the opportunity to explore this kind of manufacturing process.

Finally, the actual construction of the canopy in order to validate the fabrication process. By putting it into practice it would be possible to identify complications and make the respective adjustments to the process.

REFERENCES

[1] Mann, A. (2016) *Insight not numbers – a brief history of computing in structural engineering*, The Structural Engineer, 94 (3), pp. 10–12

[2] He L, Pritchard T, Gilbert M and Lu H (2019) *Peregrine User Manual*, LimitState Limited, Sheffield.

[3] https://www.grasshopper3d.com/ Accessed in: 24/02/2020

[4] Preisinger, C. (2013), *Linking Structure and Parametric Geometry*. Architectural Design, 83: 110-113

[5] https://www.itke.uni-stuttgart.de/research/icd-itke-research-pavilions/icd-itke-research-pavilion-2016-17/ Accessed in: 01/06/2020

[6] https://www.itke.uni-stuttgart.de/research/icd-itke-research-pavilions/icd-itke-research-pavilion-2013-14/ Accessed in: 01/06/2020

[7] Papalambros, P., & Wilde, D. (2000). *Principles of Optimal Design: Modeling and Computation*. Cambridge: Cambridge University Press.

[8] Adriaenssens, S. (Ed.), Block, P. (Ed.), Veenendaal, D. (Ed.), Williams, C. (Ed.). (2014). *Shell Structures for Architecture*. London: Routledge.

[9] Fairclough, H., Gilbert M., Thirion, C., Tyas, A., and Winslow, P. *Optimisation-driven conceptual design: case study of a large transfer truss*, The Structural Engineer, 97 (10), pp. 20-26

[10] Knippers, J. Cremers, M. Gabler, J. *Lienhard Construction manual for polymers + membranes*, Birkhäuser-Verlag (2011)

[11] Ohsaki, M. (2011). *Optimization of Finite Dimensional Structures*. Boca Raton: CRC Press

[12] Pedreschi, Remo. *Form, Force and Structure: a Brief History*. Architectural Design 78 (2008): pp 12-19.

[13] Inês Caetano, Luís Santos, António Leitão, *Computational design in architecture: Defining parametric, generative, and algorithmic design*, Frontiers of Architectural Research, Volume 9, Issue 2, 2020, pp. 287-300

[14] Cavazzuti M. (2013) Deterministic Optimization. In: *Optimization Methods*. Springer, Berlin, Heidelberg

[15] Cavazzuti M. (2013) Stochastic Optimization. In: *Optimization Methods*. Springer, Berlin, Heidelberg

[16] Sigmund, O., Maute, K. (2013) *Topology optimization approaches*. *Struct Multidisc Optim* **48, pp** 1031–1055

[17] Jj, Kingman & Tsavdaridis, Konstantinos & Toropov, Vassili. (2014). *Applications of Topology* Optimization in Structural Engineering.

[18] A.G.M. Michell M.C.E. (1904) LVIII. *The limits of economy of material in frame-structures*, Philosophical Magazine Series 6, 8(47), pp.589-597

[19] Eanamul Haque Nizam. *Applications of Fiber Reinforced Polymer Composites (FRP) in Civil Engineering*, International Journal of Advanced Structures and Geotechnical Engineering', vol. 03, July 2014

[20] Vashchuk, Alina & Fainleib, Alexander & Starostenko, Olga & Grande, Daniel. (2018). *Application of ionic liquids in thermosetting polymers: Epoxy and cyanate ester resins*. Express Polymer Letters. 12, pp. 898-917.

[21]] V. Fiore, A. Valenza,5 - *Epoxy resins as a matrix material in advanced fiber-reinforced polymer (FRP) composites*,Editor(s): Jiping Bai, In Woodhead Publishing Series in Civil and Structural Engineering, Advanced Fibre-Reinforced Polymer (FRP) Composites for Structural Applications, Woodhead Publishing, 2013, Pages 88-121

[22] Salar Bagherpour (September 26th 2012). *Fibre Reinforced Polyester Composites*, Polyester, Hosam El-Din M. Saleh, IntechOpen

[23] Liu, Yue & Zwingmann, Bernd & Schlaich, Mike. (2015). Carbon Fiber Reinforced Polymer for Cable Structures—A Review. Polymers. 7, pp. 2078-2099.

[24] https://www.itke.uni-stuttgart.de/research/built-projects/fibre-facade-prototype/ Accessed in: 12/06/2020

[25] CEN. *EN 1990: Eurocode: Basis of Structural Design*, European Committee for Standardisation, Brussels, Belgium, 2005

[26] CEN. *EN 1991-1-4: General Actions – Wind Actions*, European Committee for Standardisation, Brussels, Belgium, 2005

[27] BS NA EN 1991-1-4 (2010): UK National Annex to Eurocode 1. Actions on structures. General actions. Wind actions

[28] CEN. *EN 1991-1-3: General Actions – Snow Loads*, European Committee for Standardisation, Brussels, Belgium, 2005

[29] Cobb, F. (2015) *Structural Engineer's Pocket Book,(Third edition)*, Taylor & Francis Ltd

[30] EOTA, *ETAG 029 (2013) Guideline for European Technical Approval of Metal Injection Anchors for use in Masonry Annex C: Design Methods for Anchorages*, Brussels, Belgium

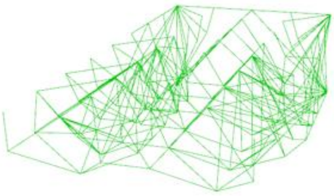
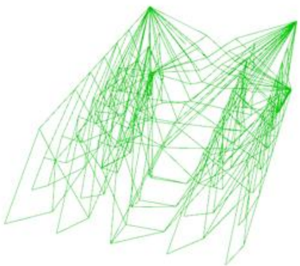
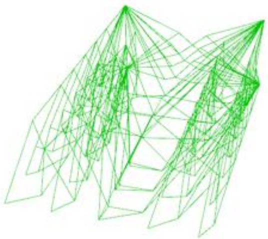
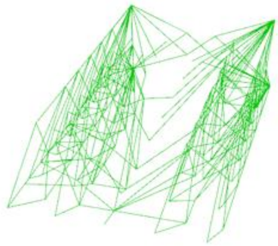
[31] Knippers, Jan & Koslowski, Valentin & Solly, James & Fildhuth, Thiemo. (2016). *Modular Coreless Filament Winding for Lightweight Systems in Architecture*

[32] La Magna, Riccardo & Waimer, Frederic & Knippers, Jan. (2014). *Coreless Winding - A Novel Fabrication Approach for FRP Based Components in Building Construction*. Proceedings of the 7th International Conference on FRP Composites in Civil Engineering, CICE 2014.

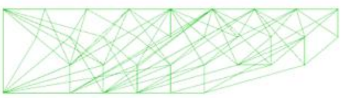
[33] Prado M., Dörstelmann M., Schwinn T., Menges A., Knippers J. (2014) *Core-Less Filament Winding*. In: McGee W., Ponce de Leon M. (eds) Robotic Fabrication in Architecture, Art and Design 2014. Springer, Cham

Annex 1

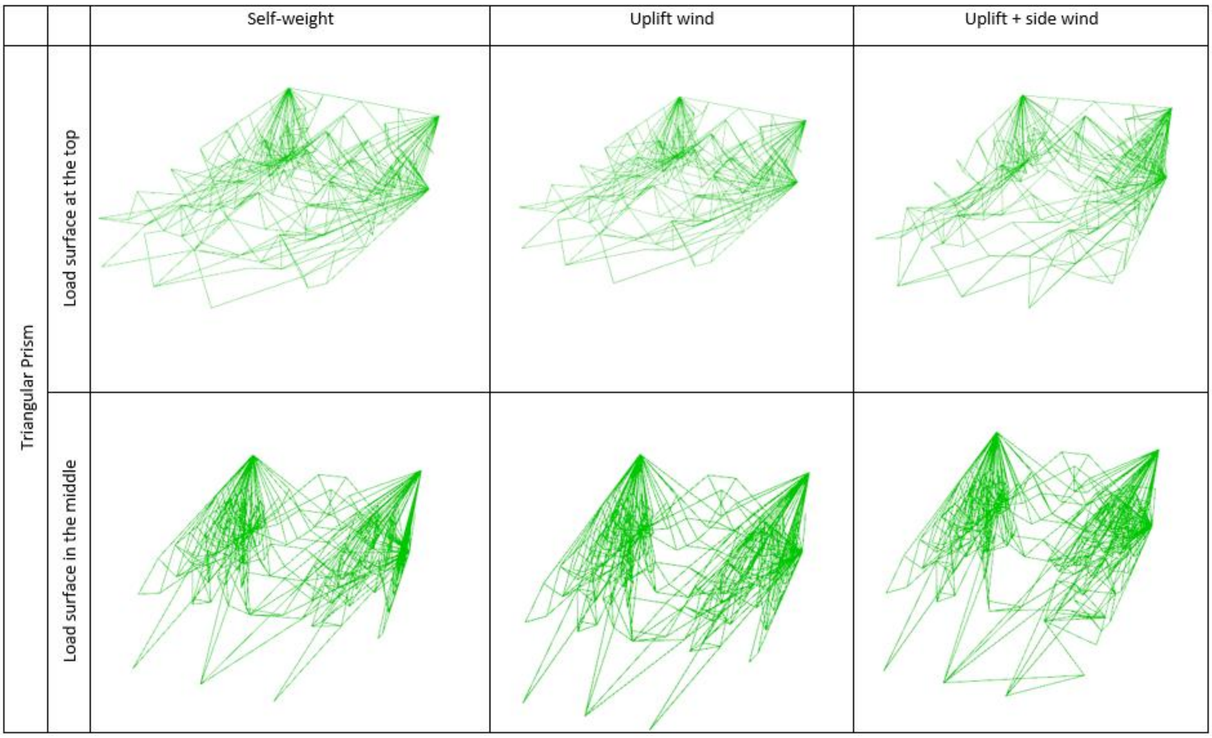
Perspective

		self-weight	Uplift wind	Uplift + side wind
Rectangular Prism	Load surface at the top			
	Load surface in the middle			

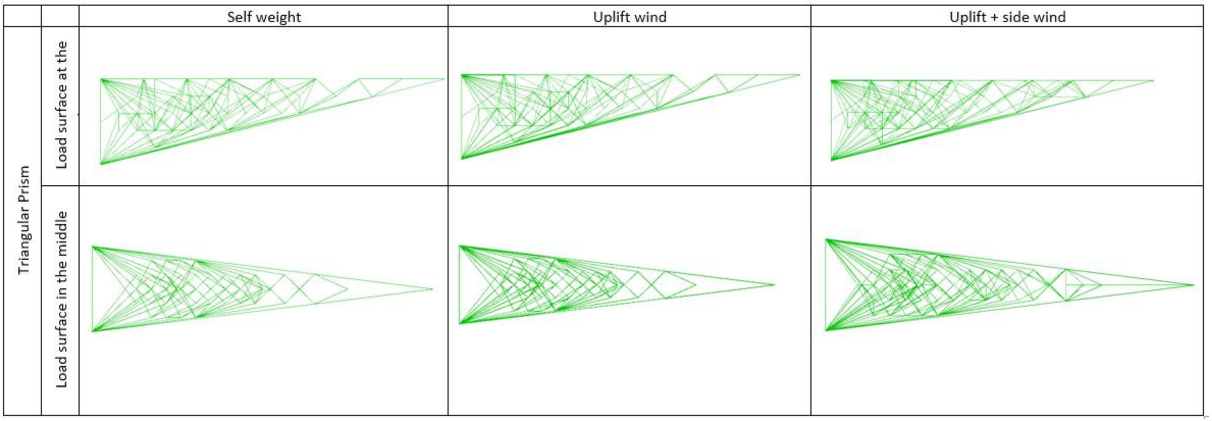
Sideview

		Self weight	Uplift wind	Uplift + side wind
Rectangular Prism	Load surface at the top			
	Load surface in the middle			

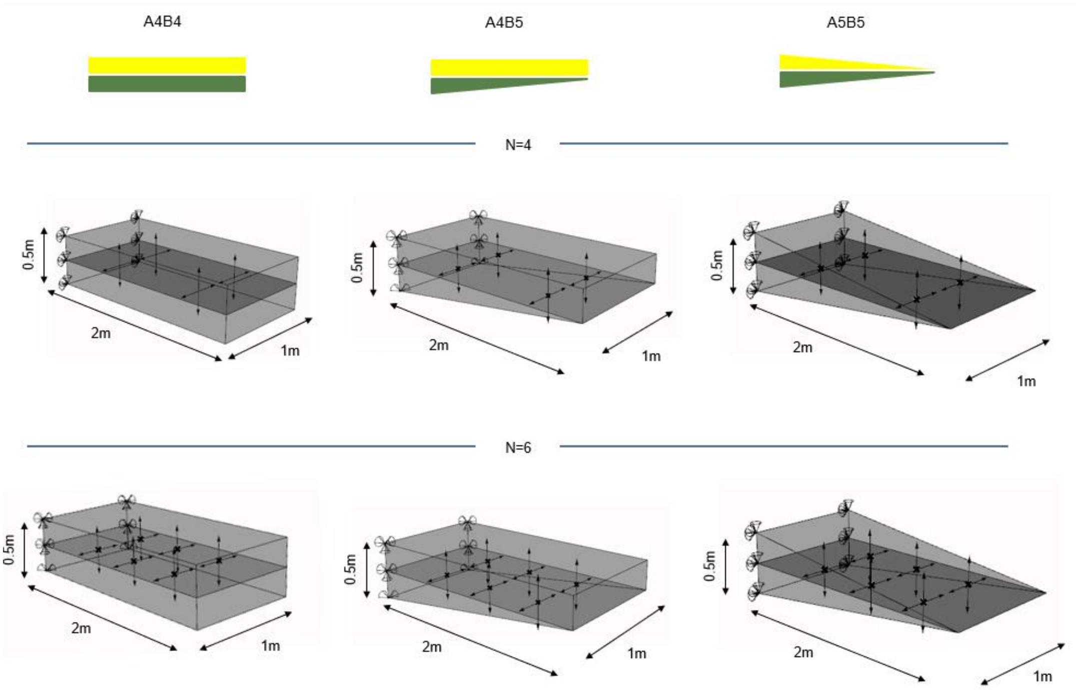
Perspective

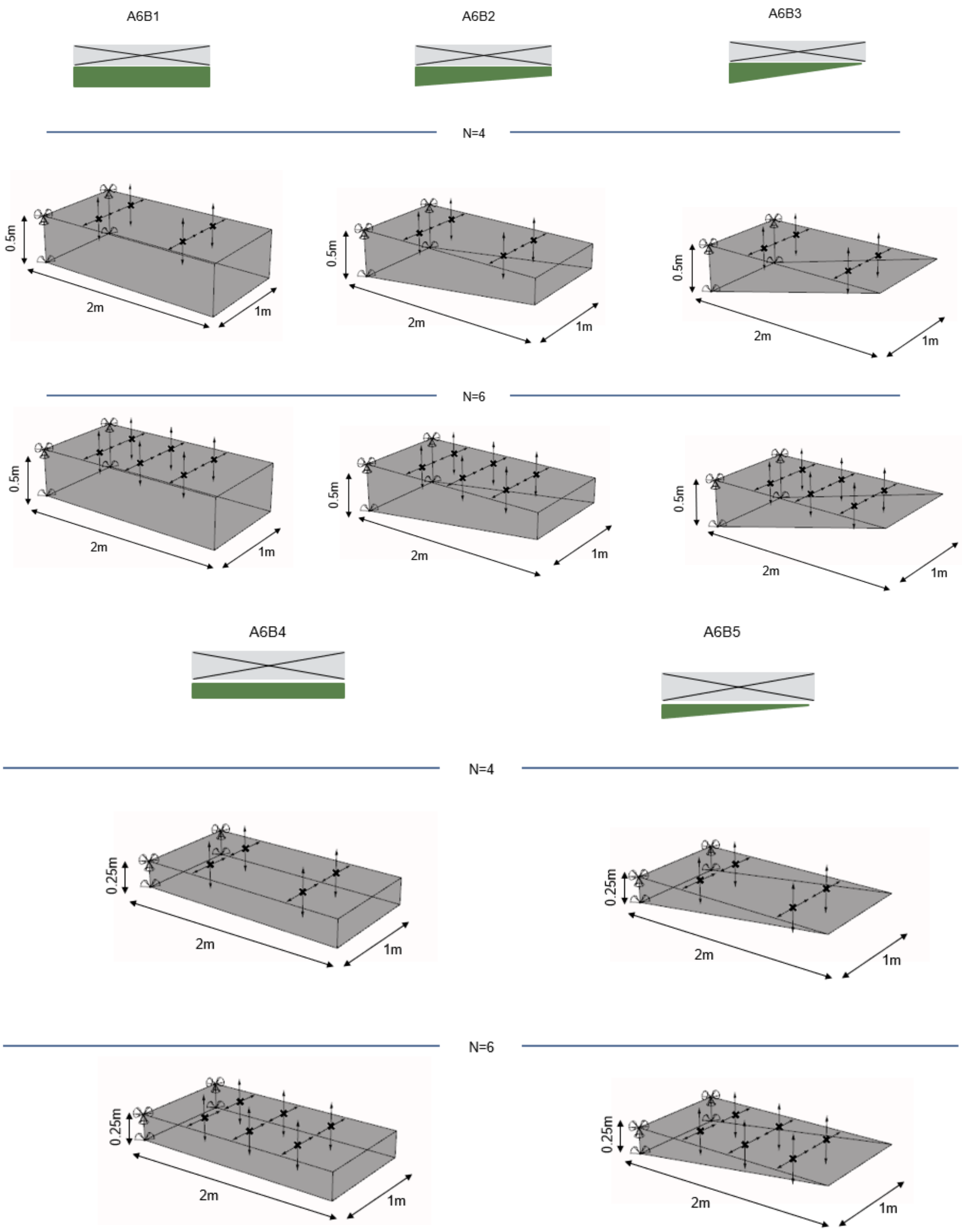


Sideview

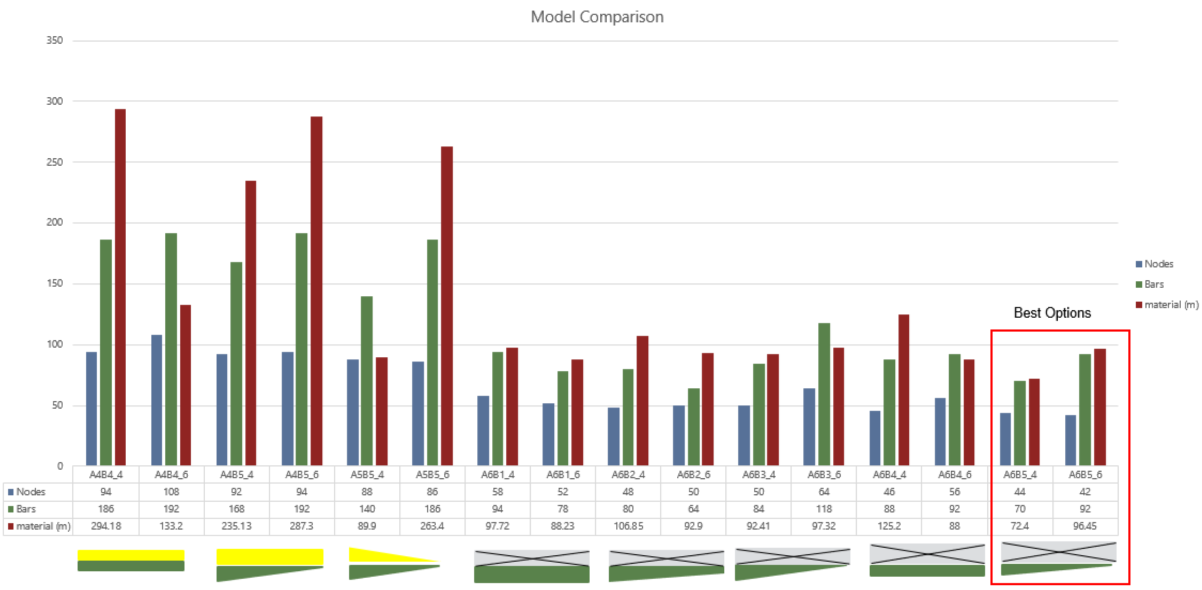


Annex 2




A6B1
A6B2
A6B3
N=4
0.5m
2m
1m
N=6
A6B4
A6B5
0.25m

Annex 3

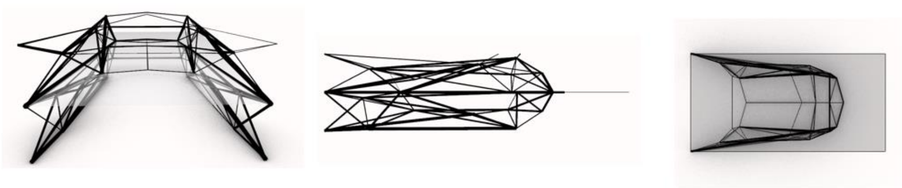


	A4B4_4	A4B4_6	A4B5_4	A4B5_6	A5B5_4	A5B5_6	A6B1_4	A6B1_6	A6B2_4	A6B2_6	A6B3_4	A6B3_6	A6B4_4	A6B4_6	A6B5_4	A6B5_6
Nodes	94	108	92	94	88	86	58	52	48	50	50	64	46	56	44	42
Bars	186	192	168	192	140	186	94	78	80	64	84	118	88	92	70	92
material (m)	294.18	133.2	235.13	287.3	89.9	263.4	97.72	88.23	106.85	92.9	92.41	97.32	125.2	88	72.4	96.45

Annex 4

A4B4

N=4



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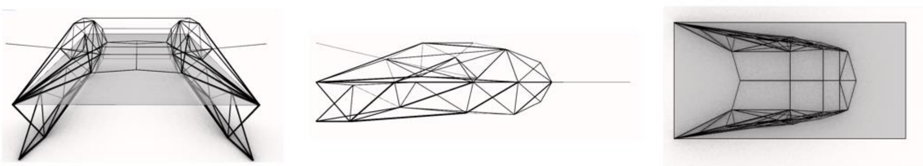
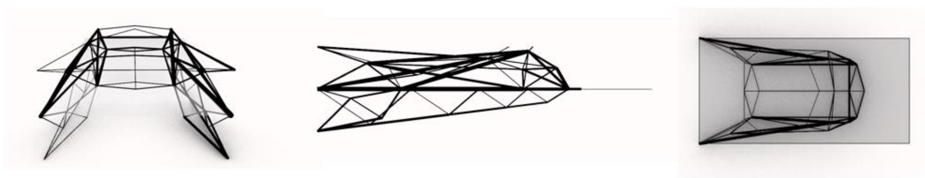
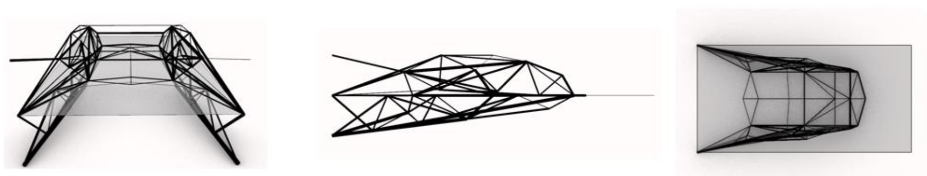


A4B5

N=4

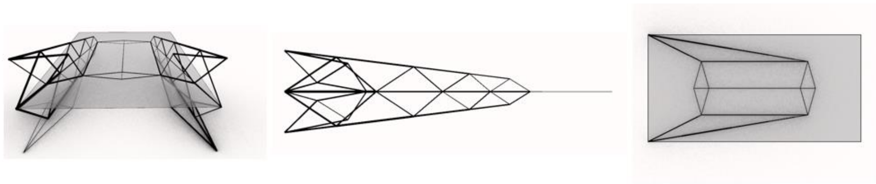


N=6



A5B5

N=4



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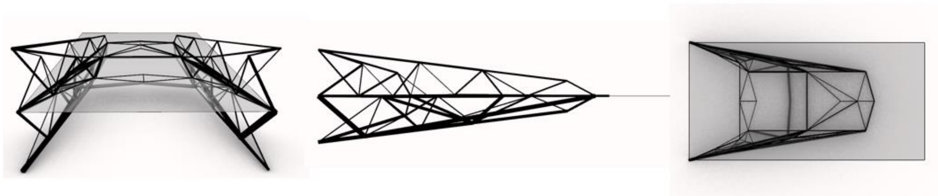
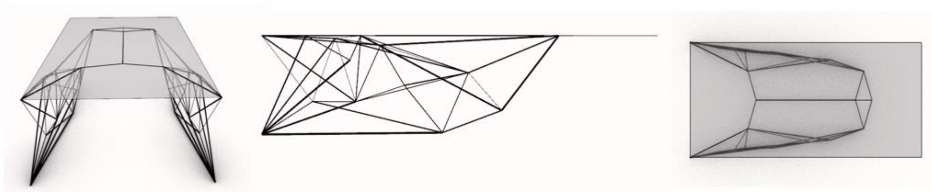


A6B1

N=4



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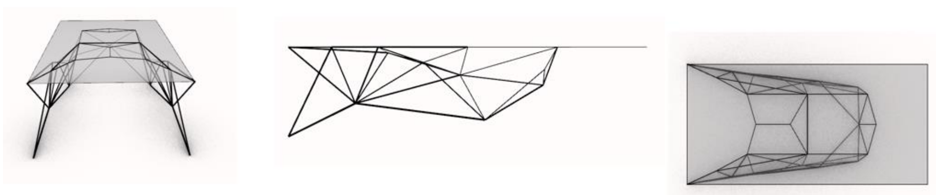
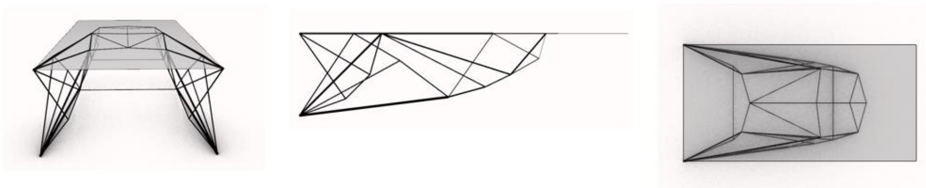
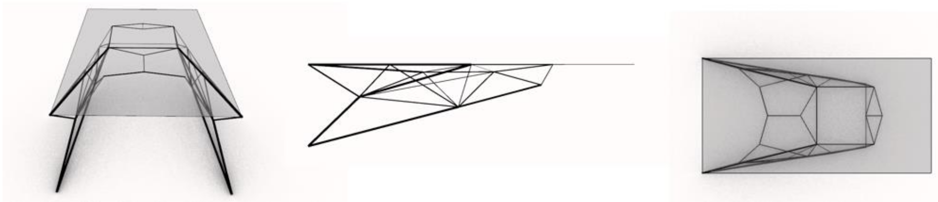


A6B2

N=4

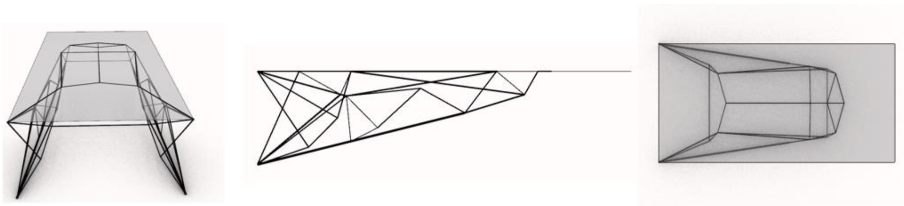


N=6

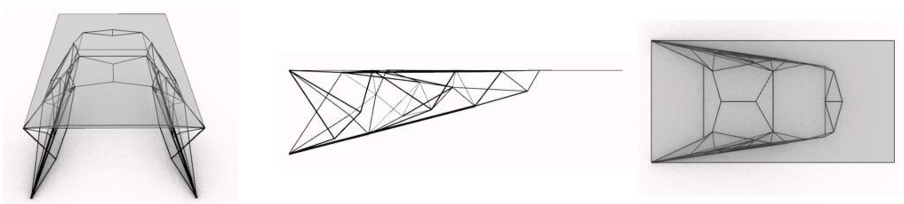


A6B3

N=4

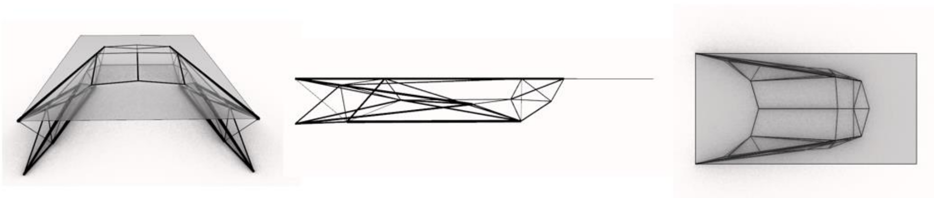


N=6

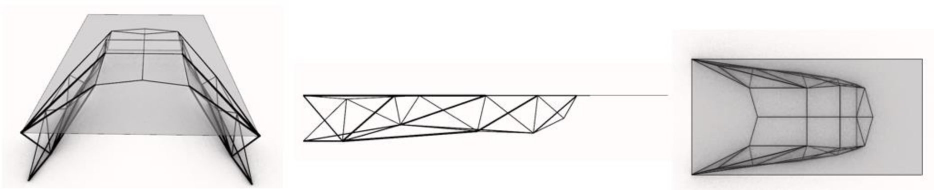


A6B4

N=4

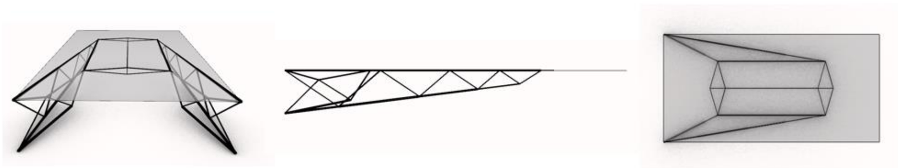


N=6

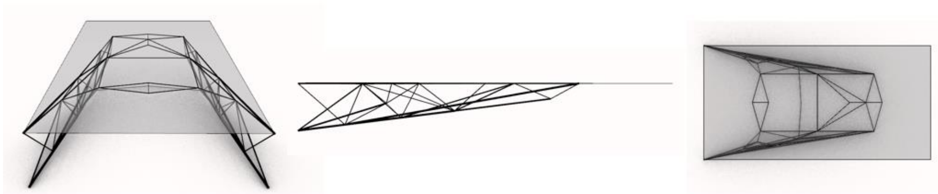


A6B5

N=4



N=6



Annex 5

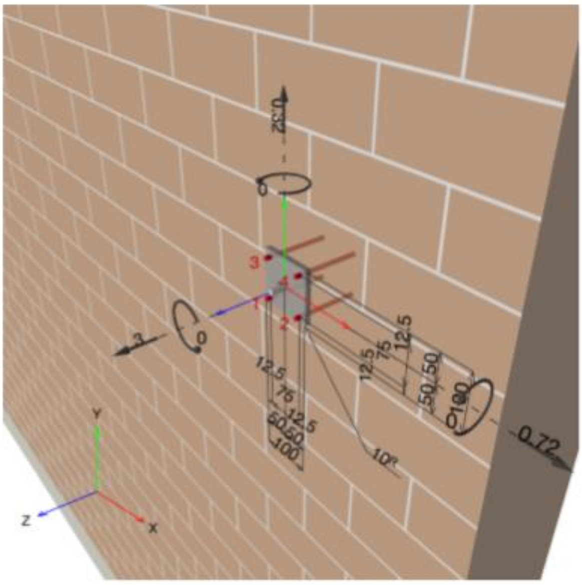
1 Input data

Anchor type and size:	**HIT-HY 270 + HAS-U 5.8 M8**
Item number:	2223854 HAS-U 5.8 M8x150 (insert) / 2092828 HIT-HY 270 (mortar)
Effective embedment depth:	$h_{ef,opti}$ = 100.0 mm ($h_{ef,limit}$ = 215.0 mm)
Material:	5.8
Approval No.:	ETA-19/0160
Issued I Valid:	30/08/2019 | -
Proof:	Design Method ETAG 029, Annex C
Stand-off installation:	e_b = 0.0 mm (no stand-off); t = 10.0 mm
Baseplate[R] :	l_x x l_y x t = 100.0 mm x 100.0 mm x 10.0 mm; (Recommended plate thickness: not calculated)
Profile:	Cylinder, 10; (L x W x T) = 10.0 mm x 10.0 mm
Base material:	Brick layout: Stretcher; Brick: Mz, 2DF, f=12 (solid brick), Clay, L x W x H: 240.0 mm x 115.0 mm x 113.0 mm; $f_{b,v}$ = 12.00 N/mm^2; E_{wall} = 3,131.77 N/mm^2 Mortar: M2,5 - M9; Vertical joints filled: YES; vertical: 5.0 mm; horizontal: 5.0 mm
Installation/Use:	Installation condition: Dry; Use condition: Dry; Cleaning: compressed air Temp. short/long: 40/24 °C

[R] - The anchor calculation is based on a rigid baseplate assumption.

Geometry [mm]

Geometry [mm] & Loading [kN, kNm]



1.1 Load combination

Case	Description	Forces [kN] / Moments [kNm]	Seismic	Fire	Max. Util. Anchor [%]
1	Load case: Design loads	$N = 3.000$; $V_x = 0.720$; $V_y = 0.320$; $M_x = 0.000$; $M_y = 0.000$; $M_z = 0.000$;	no	no	72

2 Proof I Utilisation (Governing Cases)

		Design values [kN]		Utilization	
Loading	**Proof**	**Load**	**Capacity**	**β_N / β_V [%]**	**Status**
Tension	Brick breakout	1.500	2.800	54 / -	OK
Shear	Local brick failure	-	-	- / 33	OK

Loading	β_N	β_V	α	Utilization $\beta_{N,V}$ [%]	Status
Combined tension and shear loads	0.536	0.327	1.000	72	OK

3 Warnings

- Please consider all details and hints/warnings given in the detailed report!

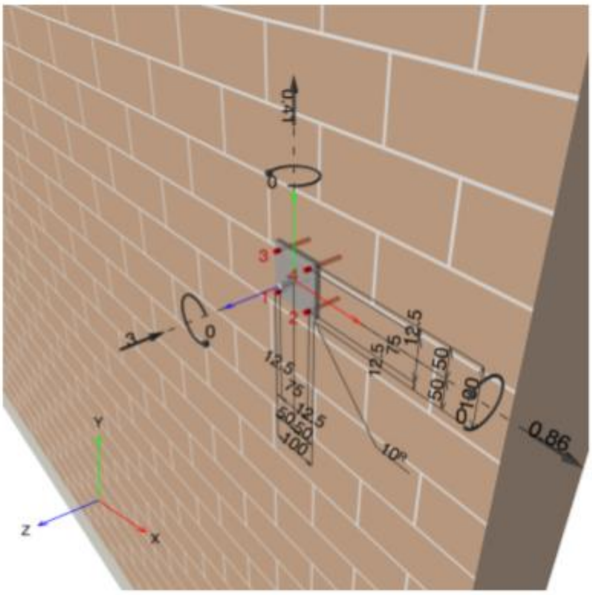
Fastening meets the design criteria!

1 Input data

Anchor type and size:	**HIT-HY 270 + HAS-U 5.8 M8**
Item number:	2223852 HAS-U 5.8 M8x80 (insert) / 2092828 HIT-HY 270 (mortar)
Effective embedment depth:	$h_{ef,opti}$ = 50.0 mm ($h_{ef,limit}$ = 215.0 mm)
Material:	5.8
Approval No.:	ETA-19/0160
Issued I Valid:	30/08/2019 | -
Proof:	Design Method ETAG 029, Annex C
Stand-off installation:	e_b = 0.0 mm (no stand-off); t = 10.0 mm
Baseplate^R :	l_x x l_y x t = 100.0 mm x 100.0 mm x 10.0 mm; (Recommended plate thickness: not calculated)
Profile:	Cylinder, 10; (L x W x T) = 10.0 mm x 10.0 mm
Base material:	Brick layout: Stretcher; Brick: Mz, 2DF, f=12 (solid brick), Clay, L x W x H: 240.0 mm x 115.0 mm x 113.0 mm;
	$f_{b,v}$ = 12.00 N/mm^2; E_{wall} = 3,131.77 N/mm^2
	Mortar: M2,5 - M9; Vertical joints filled: YES; vertical: 5.0 mm; horizontal: 5.0 mm
Installation/Use:	Installation condition: Dry; Use condition: Dry;
	Cleaning: compressed air
	Temp. short/long: 40/24 °C

^{R} - The anchor calculation is based on a rigid baseplate assumption.

Geometry [mm] & Loading [kN, kNm]



1.1 Load combination

Case	Description	Forces [kN] / Moments [kNm]	Seismic	Fire	Max. Util. Anchor [%]
1	Load case: Design loads	N = -3.000; V_x = 0.860; V_y = 0.410; M_x = 0.000; M_y = 0.000; M_z = 0.000;	no	no	57

2 Proof I Utilisation (Governing Cases)

		Design values [kN]		Utilization	
Loading	**Proof**	**Load**	**Capacity**	**β_N / β_V [%]**	**Status**
Tension	-	-	-	- / -	N/A
Shear	Local brick failure	-	-	- / 57	OK

Loading	β_N	β_V	α	Utilization $\beta_{N,V}$ [%]	Status
Combined tension and shear loads	-	-	-	-	N/A

3 Warnings

- Please consider all details and hints/warnings given in the detailed report!

Fastening meets the design criteria!