THESIS FOR THE DEGREE OF LICENTIATE OF ARCHITECTURE

Textile architecture informed by wind

ERICA HÖRTEBORN

Department of Architecture and Civil Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2020

Textile architecture informed by wind
ERICA HÖRTEBORN

Report series: Lic /Architecture and Civil Engineering /
Chalmers University of Technology
Department of Architecture and Civil Engineering
Division of Architectural Theory and Methods
Architecture and Engineering research group
Chalmers university of technology
SE-412 96 Göteborg
Sweden
Telephone: + 46 (0)31-772 1000

Cover:
Textiles knitted with a drop-stitch technique, in relaxed state and with airflow applied.
(more info in paper A, summarised on p.47).

Chalmers Reproservice
Göteborg, Sweden, 2020

ABSTRACT

Textiles in architecture is a field of great potential, which are worth to explore further. This thesis aims to show that the flexibility of the textile material could be better included in the architectural design, allowing it to adapt to forces, such as the wind, and viewing motion as a positive design feature. The main methods for this were a literature study and design investigations, using physical as well as digital prototypes, with extra focus on the material flexibility and knitted textiles. The field textile architecture informed by wind is defined through three main components: the textile material, the lightweight structure, and the wind. Textiles are, here, seen as a material with structural and aesthetical flexibility and diversity that can adapt to as well as carry applied loads. Lightweight structures are concepts for material efficiency and structural elegance. And, wind informed architecture is the concept of including the phenomena of wind in the architectural design, as a free source of energy or force that could be used, absorbed, or directed to create beauty and to form a more comfortable environment. The core of the thesis lies in the overlap of these three components. Results from this thesis indicate, firstly, that the field of textile architecture informed by wind is relatively uncharted territory. Knowledge and inspiration can, however, be found outside the field of architecture, such as performing arts, art installations, sailing, and fashion. Secondly, opportunities for supporting the, often complicated, design process of textile architecture are demonstrated through the use of a combination of digital models and physical prototypes, in the presented examples.

Key words: Textile architecture, Textiles, Wind, Lightweight structures, Knitted textiles, Geometric expression, Kinetic architecture, Research by design

Preface

My interest in textile architecture sprung from a fascination of the graceful, light, and, at the same time, strong tensile structures. Through my M.Sc. education, I developed an interest in digital simulations and how coding can open up new doors and give better control in the design process. Whether this interest led me to the clean and elegant, although structurally and geometrically complex architecture of tensile structures, or if it was the other way around, I cannot remember. It is, however, clear that these structures embody the essence of my architecture and engineering education, namely the positive results that can be achieved through the combined skills of the architect and the engineer (whether this is in one person or through a successful collaboration).

While there is undoubtingly an elegance in the tensile structures, many architects, as well as engineers, have a narrow view of textiles' capabilities within architecture (myself included, at the beginning of this research). The textile material can be soft, rough, bulky, delicate, flexible and, at the same time, incredibly strong. Yet, it seems that textiles are often reduced to either merely decorative interior elements or stretched to virtually stiff structures. A key feature of textiles is its ability to adapt to any external force. The curiosity of what could be achieved if this property was put to better use in the architectural design process has driven me throughout this research. For me, there is a beauty in the billowing motion of textiles moving in the wind or how clothes can sometimes flow around the body. It is intriguing to think about what would happen if this feature was used more in built architecture.

The work that leads up to this licentiate thesis has been a rewarding but also a challenging journey. Especially the decision to factor in the wind in the design has put me to test. This thesis only scratches the surface of the complexity in the mathematics and physics behind the phenomena of wind. Also, figuring out how to physically work with, and document, the wind has proven to be an intricate task. Where finding the space and time to use a wind machine might have been the easiest part. Adding wind as an aspect in a design automatically factors in time in the equation, as wind is essentially airflow over time. Neither the wind, nor time is something we can see, yet we can see the effects of them. In the documentary *Rivers and Tides*, with the subtitle *working with time*, the artist Andy Goldsworthy says, about one of his pieces (and the 'destruction' of it), 'that's a way of understanding, for me, seeing something you never saw before, that was always there, but you were blind to'. (Riedelsheimer, 2001). Through his work with nature and especially the flows he aims to visualise the place. In the same manner textiles can be thought of as a way to visualise wind and showing the beauty in it.

It is my hope that this thesis can start to widen the view of the potentials of the textile material within architecture, both aesthetically and structurally.

Erica Hörteborn, Varberg, 19 October 2020

ACKNOWLEDGEMENTS

First of all, I am extremely grateful to my examiner Professor Karl-Gunnar Olsson, whose support and guidance have been invaluable during, not only, the work with this thesis, but throughout my higher academic education. Without your confidence in me, I would not even have started this journey towards a PhD.

I also thank my supervisors, Dr. Chris Williams, Dr. Mats Ander, and Dr. Malgorzata Zboinska, your support and insightful feedback pushed me to sharpen my thinking and brought my work to a higher level. I am very grateful for the inspiration that you have given me, Chris, and for your ability to explain even the most complex physics in simple and understandable terms. I would like to give a special thanks to Mats for your enthusiasm and ability to give me the confidence that I will manage the tasks at hand. Finally, I am thankful for Malgorzata's helpful advice, especially when it came to formulating the research questions and methodology.

I would also like to extend my gratitude to the Chalmers University of Technology Foundation for the funding opportunity to undertake my Ph.D. education.

Peter Christensson, I highly value the many interesting talks that we have had around my research and your amazing ability to look at questions from so many unexpected angles. I also want to thank Professor Delia Dumitrescu for your support and for broadening my view of knitted textiles.

I want to thank several people at Chalmers for their support, feedback, inspiring discussions, and help, including Morten Lund, Maja Kovacs, Tabita Nilsson, Peter Lindblom, and my fellow PhD colleges, especially, lic. Alexander Sehlström, Jens Olsson, Emil Adiels, Dr. Elke Miedema, and Saga Karlsson. During 2018 and 2019, I had the privilege to act as supervisor for Linda Wallander and Malin Borgny, your inspiring work with textiles from different angles and the discussions around it gave insights to this research and I highly value the positive energy you brought. The list of people that I would wish to thank is long and space here is limited. Have you ever given feedback to me, shown interest or given support during any of my, seemingly weird, explorations at Ljusgården, or just stopped for some small talk, then you are one of those people that I would have liked to mention here. Thank you for making Chalmers a fun and inspiring place to work at!

Last but certainly not least, I could never have done this without the unconditional love and support from my family. I am especially thankful to my amazing husband Axel Hörteborn. I love you all!

Erica Hörteborn, Varberg, 19 October 2020

THESIS

This thesis consists of an extended summary of the research field and the following appended papers:

Paper A

Hörteborn, E., & Zboinska, M. (2020). Exploring expressive and functional capacities of knitted textiles exposed to wind influence [Manuscript submitted for publication].

Paper B

Hörteborn, E., Zboinska, M., Dumitrescu, D., Williams, C., & Benjamin Felbrich. (2019). Architecture from textiles in motion. Form and Force, 2316–2323.

Paper C

Henrysson, E., Olsson, J., Fisher, A., & Ander, M. (2016). Conceptual design and analysis of membrane structures. 29th Nordic Seminar on Computational Mechanics, S8:2:c.

CONTENTS

1 Introduction

There is something intriguing in the way a textile moves in the wind - or around a moving body. Soft materials like textiles take on the shape governed by applied forces and constraints. In Figure 1-1 the constraint is the dancer, Arika Yamada, and the main forces are the pressure from the wind around her and the textile. Here the textile became a partner in the dance. In a workshop with master students in the architecture design studio Matter space structure, at Chalmers, the students worked with designing space with textiles in motion. One student reflected that when sitting in the textile room, with the textiles softly moving in the wind: “If I’d be sitting alone in a space like this, I would not feel lonely” (Figure 1-2). By that she meant that the movement in the textile made it feel like a friendly presence that kept you company.

Figure 1-1 Arika Yamada dancing, exploring textile in wind

The material flexibility of textiles is a property that is hardly used within architecture today, except in interior architecture. In general, the concept textile architecture is associated with fabric that is stretched until it is virtually stiff, creating a seemingly static structure even in strong wind. Such textile structures are, with some exceptions, limited to an anticlastic (double-curved) geometry. However, a broader use of textiles is possible. Textiles, with a looser fit, could be used as elements in a roof, a wall, or a façade:

- as a semi-transparent or semi-translucent shielding for light, sound, and/or wind
- to absorb/dissolve wind energy for an improved microclimate
- to define a space and develop the geometric conception of a room
- and not at least, as means for expression and tactility.

The flexible textile introduces an architectural material that allows for both new shapes and movements as architectural expression and spatial experience.

The hypothesis is that architecture can gain a lot from embracing the flexibility of textiles as well as better incorporating the dynamic element of wind in the architectural design. Architecture can, by using textiles, take advantage of, move with, and benefit from the power in the wind.

Figure 1-2 A textile room designed within a student workshop.

1.1 Aim

This thesis aims to investigate the field of textile architecture, mainly focusing on flexible textile elements. The investigation consists of three parts:

- A suggestion for a systematic description of the field textile architecture and wind.
- A brief overview of the physical phenomena that governs the interactive behaviour between textile and wind, and some numerical methods for simulation of stiff as well as flexible textiles to be used in the architectural design process.
- A suggestion for a systematic use of prototypes in an explorative design process to support the investigation of textiles and wind.

Associated research questions are:

- How can the field textile architecture and wind be systematically described to clarify central aspects of textiles and wind in architecture and through them act as inspiration for new applications?

- How can an architectural design process, for stiff and/or flexible textiles, be supported by digital (numerical) tools, appropriate representations, and explorative use of prototypes?

1.2 Textile architecture and wind

In order to systematically investigate the field of textile architecture and wind three core elements of the field was defined:

- Textile as a material with structural and aesthetical flexibility and diversity that can adapt to as well as carry applied loads.
- Lightweight structures as a concept for a material efficiency as well as flexible construction and structural elegance.
- Wind informed architecture as a concept of including the phenomena of wind in the architectural design, as a free source of energy or force that could be used, absorbed or directed to create beauty or to form a more comfortable environment.

All investigated from an architectural perspective (Figure 1-3). The circles, in the diagram below, and the overlaps of the fields, two by two, are defined and elaborated in chapter 2, which is concluded with the intersection of all circles - *textile architecture and wind* - the core of the field.

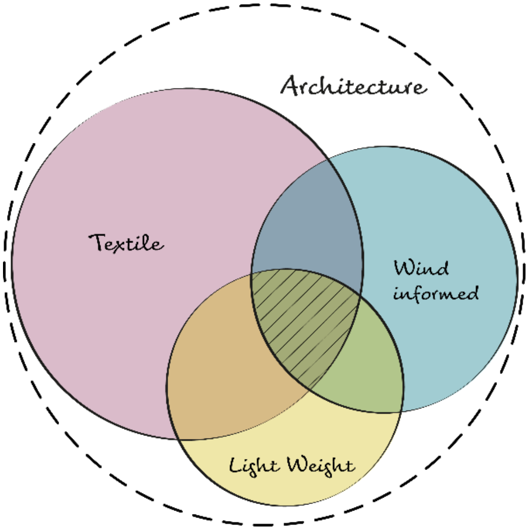


Figure 1-3 The area of investigation.

1.3 Research environment and background of the researcher

With an education both as a structural engineer and as an architect, I apply working methods and thinking from both fields throughout my research. This, in itself, could classify as cross-disciplinary work. In addition, the research is communicated with, and inspired by, people and through venues in both fields, as well as in the field of textile design. The latter being a field that I am somewhat new to but where I am, through my research, starting up collaborations and have come across, for me, new ways of working with textiles, both when it comes to how we use textiles as well as what the textile material could be. Examples of such venues and collaborations are The Swedish School of Textiles – University of Borås and the research network ArcInTex (connecting the fields of architecture, interaction design and textiles), and the engineering firm Buro Happold.

I am a member of the newly established research group "Architecture and Engineering" and have a degree (MSc) in both architecture and structural engineering from the bachelor and master program with the same name. Both the education and the research group focus on how spaces and architectural expressions interact with materials and loadbearing structures. Significant for the group is also the mathematical modelling combined with building digital and physical prototypes to explore and communicate designs. The research group has been involved in arranging conferences like AAG (Advances in Architectural Geometry) and Smart Geometry and are frequently participating in the IASS conferences (International Conference on Spatial Structures).

This environment inspired me to start working with tensile textile architecture and eventually explore more sides of textiles within an architectural context. I have also supervised master thesis projects where the textile material and textile approaches for architecture have been explored. The system that is used to describe the research field, of this thesis, is sprung from approaches used within the research group, i.e. the way of using mathematical models to simulate phenomena and the open-ended explorations.

1.4 Overview of the thesis

This introduction chapter is followed by chapter 2 containing a contextualisation of the research. Defining the main components of the research field in order to outline its core. The methods used in this thesis, as well as a short reflection around them, are then described in chapter 0. This is followed by summaries of the three appended research papers (chapter 0). Finally, chapter 0 outlines the main conclusions and discusses core elements of the research as well as relating it to the debate around sustainable development and research ethics, and gives suggestions for future research.

2 Textile architecture and wind from different perspectives

In this thesis, the field of *textile architecture designed to move with the wind* will be defined as the intersection between the three components "textile", "wind", and "lightweight", all of them in an architectural context (Figure 2-1). Sections 2.1-2.3 will give a context for the three concepts through a collection of examples, characteristic properties, and digital design tools for simulation. Similarly, the intersections between the components are defined and explored: 2.4 "tensile structures", 2.5 "wind in combination with textiles" and 2.6 "kinetic architecture". Sections 2.1-2.6 have three subsections each, the first describes examples from the field, while the second talks more about the phenomena and the third subsection brings up ways to simulate the interactions between forces, the material, and movement.

Finally, the intersection of all the three components will be discussed in order to describe and explain the specific research field that this thesis aims to explore.

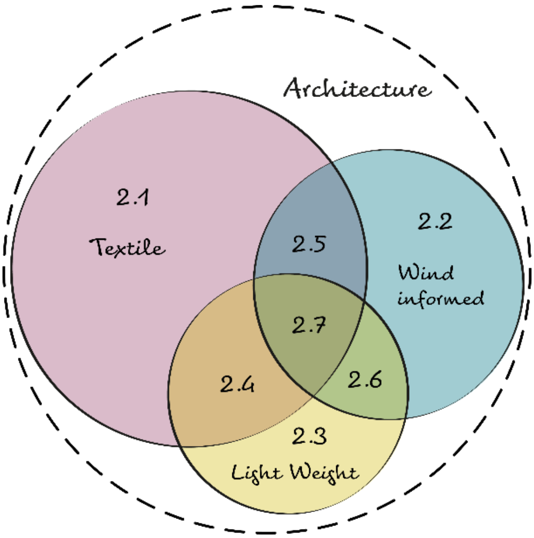


Figure 2-1 the research field and structure of this chapter of the thesis

2.1 Textiles in architecture

There is a range of possible definitions of textile architecture, however few authors give a definition. One is given by Garcia (2006) who categories textiles in architecture based on forms of architecture-textile relationships. His three different types of 'architextiles', as he calls them, is;

> ‘when a textile or textile-based process is used as a metaphor, when a textile-like spatial structure (such as a weave) is produced in architecture, when textiles (or textile composites) are used as a real material in a real building, and where textiles appear in architectural theory and texts’ (Garcia, 2006, p. 13).

This thesis will focus on Garcia’s third architecture-textile relationship; when textiles are used as a building material, with a specific focus on woven and knitted, flexible textiles.

Within this field, textiles are used for a wide range of purposes, ranging from pure decoration to vital construction. In the book *Textile architecture* (2009), Sylvie Krüger divides textile architecture into 3 main categories based on their function for space; vertical, horizontal, and three-dimensional space definer. These are in turn subcategories based on their functionalities. A variety of materials and structures are used for structures within all of Krüger’s categories, but the examples are limited to structures that use flexible textile materials. Her system of classification does not separate the architecture based on the behaviour of the textiles, like, for example, loosely fitted or stretched fabric.

2.1.1 Textile architecture: from prehistoric to present

Throughout history textiles have been used as weather and visual protection in a wide range of ways. In fact the basic tent can be traced back to prehistoric times. 150 000 years old remains found at Grotte du Lazaret, Nice, France, shows evidence of primitive shelters consisting of upright poles against a rock wall covered with animal skins (Kronenburg, 2014). The Bible, Exodus 26.1-37 (the Bible, Swedish translation, 1999) gives a detailed description of how the tent of the Lord's presence were to be constructed, describing both structure and room composition but also colours and embroidery. In this story, textiles were used partly because this was a temple that had to be portable, since the Israelites were wandering the desert at this period, however, it also suggests that textile used to be a significant, and sometimes luxurious, building material, for shade and insulation, as well as being a decorative material. Though the Bible should not be taken as an exact historic document the fact that this detailed description has survived and is included in the book indicates the importance of the structure. Gottfried Semper even claims that the original, and true, wall are textile (Semper, 2010). In the book *the four elements of architecture* he separates, what he believes is the true function of the wall, the provision of enclosure, from the load carrying structure. Arguing that, as the wall originates from woven branches and bast mats,

> ‘Hanging carpets remained the true walls, the visible boundaries of space. The often solid walls behind them were necessary for reasons that had nothing to do with the creation of space; they were needed for security, for supporting the load, for their permanence, and so on.’ (Semper, 2010, p. 104)

Semper also relates the German words *wand* [wall] to the word *gewand* [dress], which he states, indicates that walls were originally made up by woven materials, as clothing is.

By looking at how tents are constructed and used in nomadic cultures, we get an understanding of the importance of textiles for providing shelter in prehistoric times, before humans began to settle. As people started to erect more solid dwellings, textiles lost significance as a building material and was mainly used for festive and courtly occasions and, perhaps especially, military camps. During first the Roman and later the Ottoman empire, with huge demands for military tents, the art of tent construction for military purposes developed and has conditioned to advance until today. Techniques that also has developed the tents for recreational camping. In the mid-20th century, Frei Otto showed that textile structures could also be permanent structures, through his work with tensile cable net and membrane structures (Krüger, 2009). With their design of the German pavilion at the 1967 World Expo in Montreal, Frei Otto and Rolf Gutebrod started a new chapter in the history of textile structures. The pavilion had 'a tent-like roof made of a net of cables' and was chosen by Germany because the lightweight construction which would be economical to transport overseas (Klaus-Michael Koch, Karl J Habermann, 2004). Although the original design was a tensile membrane structure, it was finally built as a cable net structure, using the membrane as a secondary cover. The expo pavilion was the inspiration for the Olympia roof in Munich, 1972 (Klaus-Michael Koch, Karl J Habermann, 2004) (Figure 2-2), designed by engineers and architects: Günther Behnisch, Frei Otto, Fritz Leonhardt, Jörg Schlaich, John Hadji Argyris, Klaus Linkwitz et el. (Tomlow, 2016). This was the first cable net structure ever done in this scale, and with it, research in both computational form-finding methods and computational structural analysis were taken to a new level (Bechthold, 2008). Thus, it is an important building in the history of textile structures, even though it is not strictly speaking, a textile structure.

Figure 2-2 Münich Olympic stadium, built for the 1972 Olympics, designed by Günther Behnisch, Frei Otto, Fritz Leonhardt, Jörg Schlaich, John Hadji Argyris, Klaus Linkwitz et al..

2.1.2 The textile material

While most of us “know” what qualifies as being textile, no universal definition seems to exist. Depending on the classification, a wide range of materials can be counted as textiles, with several materials on the border of being textiles. As an example, the definition “textile is a woven structure” would, include a lot of the materials that we call textile, around us in our everyday life. However, it is unclear if a knitted fabric is included in this definition while a woven basket or a willow fence should be considered textile. Furthermore, it leaves out the non-woven fabrics, like felted structures.

In this thesis textile is defined as a material that:

- have a thickness that is much smaller than length and breadth.
- consists of fibres or structural members that in some way interlock and would, to some extent, unravel if one “tread” were to break.
- Are only able to carry load through tension and have low bending stiffness.

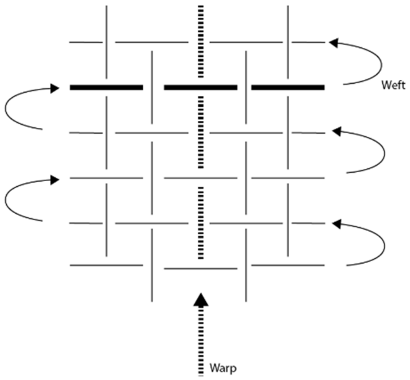
According to this definition, a textile stop being textile if it, for example is cast in concrete. The concrete façade and glass piece in Figure 2-5 are examples of structures that would be considered to just mimic textiles. They could, however, be considered to be included in Garcia’s third type of ‘architextiles’ (section 2.1).

Structures that comply with two out of the three points in the list above would be classified as textile-like. Examples of such are ETFE plastic membranes, which are flexible and thin but a homogenous material. Similarly, woven baskets and willow fences, which are woven and thin, but not flexible are classified as textile-like.

Figure 2-3 Left: The facade artwork, Touch (Sydney), by artist Dani Marti, at Westfield Centrepoint Sydney, is a concrete cast, but gives the illusion of being a weave.
Right: Glass blown into a textile mold (piece created at the ArcInTex workshop *Material pairings*, Edinburg 2018)

There are three principal methods of forming yarns into a textile: interweaving (i.e. producing woven structures), intertwining (e.g. braiding and knotting) and interloping (e.g. knitting) (Spencer, 2001). This thesis will focus on biaxial woven and (weft-)knitted[1] textile structures. Both can be seen as a repetition of joints (Figure 2-4). The basic weave consists of the warp in which the weft (sometimes referred to as fill) is inserted, woven over and under the treads of the warp. Depending on how many and which treads the warp pass over and under different patterns are created.

Most examples of textiles in architecture use a woven textile, and applications of knitted structures are scarce. The stability and stiffness of a woven textile is more directly linked to the thread strength and stiffness, compared to a knitted textile, since the threads in the weave are close to straight. In a knit, the thread is forming linking loops, and, as a result of this, larger deformations of the textile occurs when forces are applied. The knitted structure can be varied to a great extent in order to create desired aesthetic and structural properties. In all textiles the links, between the treads, in the material relies on friction. Thus, the length between the links/"nodes" could be altered with force, creating "holes" in the material, without breaking it.



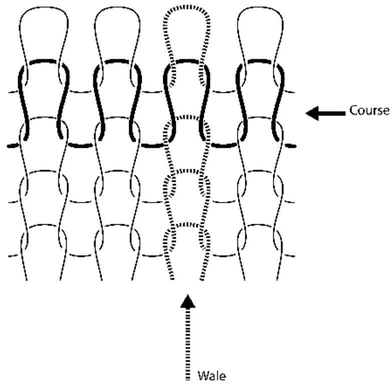


Figure 2-4 Structural logic of textiles. Left: weave consisting of warp and weft. Right: Single Jersey knit, showing course and wale dictions.

2.1.3 Simulating the mechanical behaviour of the textile material

Typically, mechanical simulations of textiles require a model that can handle local orthotropy of the material as well as the mechanisms connected to the specific textile structure. As a weave is built up through warp and weft, and a knit with loops organized in courses and wales. Depending on what level and scale, that are of interest, different methods will be appropriate. Generally, for textiles within architecture, the deformation of interest is on a larger scale compared to stitch and surface level. Thus, the textile is generally simplified into a continuous surface or a courser mesh, that carries information about the material properties, such as stiffness, in different directions. This will be further

[1] In this thesis it is implied that knitted structures = weft knitted. The method and structure of warp-knitting is not discussed

elaborated in section 2.4, and simulations of moving, loosely fitted, textiles, on a larger scale, will be discussed in section 2.5.3.

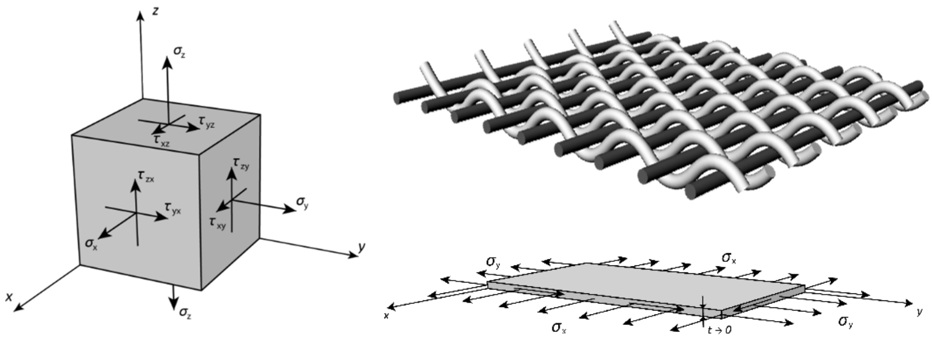


Figure 2-5 a) Stresses in an idealised 3D material. b) The weave of a textile, where the warp is drawn in black and weft in white c) Stresses in an idealised 2D membrane

On a weave/stitch level, the textile could also be simulated as a set of nodes, positioned in the intersection of the threads in the textile (Figure 2-6). On a knitted textile, each individual knitted stitch and the friction between the loops have a bigger impact on the textile, compared to the woven structure, which is built up by several threads acting in parallel. Therefore, this method is perhaps more appropriate for knitted structures. One example of such a model is demonstrated by (Cirio et al., 2017). They are doing artistic simulations, for computer graphics, of different knits and deformations of them, on a stitch level. Also including unravelling of the grid through pulling out treads. The same type of grid structure could also be used for a structural FEA model of plain knits (Araújo et al., 2004). On an architectural scale (Schmeck & Gengnagel, 2016) are using a similar approach, but using a courser hexagonal grid. Thus, having sufficient resolution to generate good analysis data, while keeping the computations light enough to be useful in a conceptual design stage.

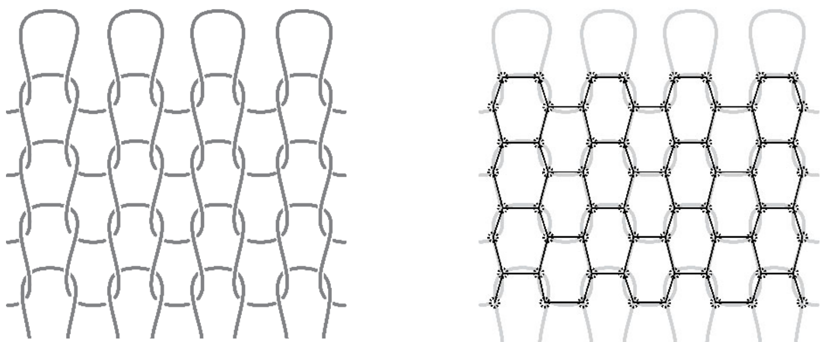


Figure 2-6 A plain knit structure (single jersey) and the translation into a hexagonal grid of nodes.

2.2 Architecture informed by wind

This section will give a few examples of how wind has been included in design of space, shape and expression. The examples could be divided into four categories depending on their interaction/approach to wind:

- Design of the wind environment around the building. Room and wind.
- Wind as an active part of the ventilation. Indoor climate and wind.
- Designing the building to reduce wind loads on the structure itself. Shape and wind.
- Using the wind as a design material. Expression/movement and wind.

This will be followed by a short introduction to the behaviour of wind around objects and basic concepts of fluid dynamics. Ending with short information about different methods for computational fluid dynamics (CFD).

2.2.1 Shaping the wind and shaped by the wind

Wind can be redirected or dampened by different types of barriers and structures, both to create a shielded, calm space, or to use the wind for cooling or as a driver. Windbreaks to shield a place from harsh winds, and create a more comfortable environment, could be designed in many ways. A wall that blocks all wind could seem like a good idea, but it could potentially make the wind situation worse by creating turbulence and/or moving the problem somewhere else. Trees and bushes are examples of efficient porous structures, that redirect some of the wind and filters and dampens parts of it. Windbreaks can, also, simultanoiursly both create a more comfortable environment, as well as use the wind to create a kinetic structure (Moya et al., 2013, 2014).

Instead of blocking the wind to create a comfortable wind environment the 30 St Mary Axe, a.k.a. the Gherkin, in London, has a circular floorplan, to minimize turbulence that otherwise is common around tall buildings. With spiralling airshafts it is also designed to naturally ventilate the building, thus reducing the energy demand (Freiberger, 2007). Similarly, the Jean-Marie Tjibaou Cultural Center, designed by Renzo Piano, is carefully designed both for the exterior and interior environment. Both to shield from monsoon winds from the oceans as well as achieving natural ventilation. Although (Wu et al., 2011) have later done wind simulations which, they claim, proves that the design might not be perfectly designed from a wind perspective. Another example of passive ventilation is windcatcher towers, which bring down the wind and fresh air into a building (Bahadori, 1978). It is a passive tool that has been the main cooling system for thousands of years in the Persian Gulf region and in the north of Africa (Saadatian et al., 2012). They could be designed with one or multiple openings, as an example the traditional (Persian) Baud-Geer windcatchers are normally divided into four quadrants. Examples of modern architecture using the same design ideas can also be found. The University of Qatar, in Doha, is one example, here the wind towers are designed to absorb the wind power to produce electricity (Saadatian et al., 2012).

Artists like Ned Kahn, Theo Jansen, and Antony Howe all use the wind in their creations, as a driver for motion and as something that adds another dimension to them. Kahn's ever-changing facades, the perfectly balanced, mesmerizing sculptures by Howe and the curious Strandbeests by Jansen all uses the wind to enrich our environment, and to invoke curiosity.

Cars and airplanes have designs that are, in a way shaped by the wind, as the goal is to direct the wind to create a lifting power and to reduce drag. One example of a streamline shaped building is the Glasgow tower (Figure 2-7). The profile of the tower is designed as an airplane wing to minimize the wind loads and achieve a steady wake, but it is also designed to rotate according to wind direction (Liddell & Heppel, 2001). There have however been several problems with the tower, including the rotating base (Brocklehurst, 2013).

a)

b)

Figure 2-7

a) Tjibaou cultural center, centre culturel Tjibaou Nouméa, New Caledonia. Designed to shield from harsh monsoon winds as well as enabling natural ventilation

b) Glasgow tower. Completed in 2001, the 127m high tower can rotate 360 degrees to reduce wind loads on the structure.

2.2.2 Fluid motion

Wind can blow in all directions, horizontally, vertically and in swirls. The motion of air is, usually, caused by differences in pressure, and the strive to even these. On a global scale the pressure difference is caused by warm air around the equator having higher pressure than the colder air around the poles. Wind speed also varies with height above the ground. Therefore, wind is usually described with a *wind profile* which shows the mean velocity at height, z, above ground. An example of a typical profile, for a turbulent boundary layer is illustrated with a dashed line on the left in Figure 2-8 (Aynsley, 1999). The mean velocity is typically based on statistical wind data gathered over time. Because of friction the velocity of the air close to an object is the same as the velocity of the object itself. In the case of wind close to the ground, the velocity is zero. The roughness of the surface determines how far this affect is noticeable, i.e. the thickness of the *boundary layer* where viscous forces are significant. Above this there is no velocity increase with the increase in altitude. As an example, a city with tall buildings is classified as a “rough surface” compared to a costal landscape where the wind speed will increase quicker with height.

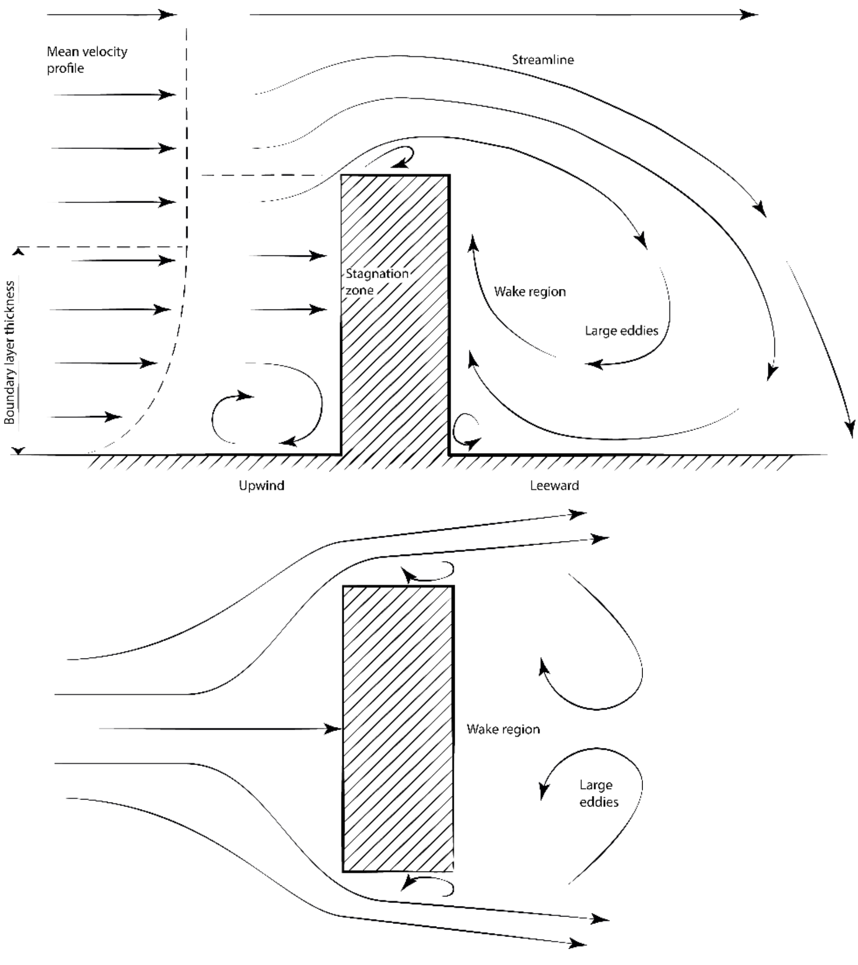


Figure 2-8 2D simplification of wind flow around a building, in a cross-section and a plan view.

To some extent, the wind will blow in the direction with the least resistance. Upwind of a building there will be a high pressure due to the wind force pushing up against the building. On the leeward side, the *wake region*, there will be a low pressure which will "such down" the wind and eventually create a *vortex.*

Wind behaviour can be described through Navier-Stokes equations, which are essentially based on Newtons 2nd law of motion, $F = ma$ (force is equal to mass times acceleration) and the conservation of mass i.e. the mass of a fluid body is constant. These equations can be found in 0, as well as brief mathematical description of some of the terms in the equations. For an irrotational and steady flow, where viscous forces are negligible the Navier-Stokes equations can be simplified into the Bernoulli's equation (2-1), which says that the sum of the pressure, p, the kinetic energy, $\frac{1}{2}\rho v^2$, and the potential energy, $\rho g z$, along a *stream line*, should be constant (i.e. conservation of energy). Where ρ is the density of the fluid/gas, g the gravitational constant, both of which are, in many cases, considered to be constants. z is the vertical distance. Bernoulli's equation shows that the pressure is at a maximum in the *stagnation zone*, in Figure 2-8, where the velocity is equal to zero, and the simplification make it not applicable in the wake region.

$$p + \frac{1}{2}\rho v^2 + \rho g z = C \qquad (2\text{-}1)$$

The lift of an aerofoil (aeroplane wing) could be explained (in 2D) by the fact that its geometry causes wind to be deflected downwards. As the wind is pushed down, then there will be a reaction force lifting the wing up. Wind is deflected down since the wind strives to attached to the surface of the wing, same as water follows the surface of a cylinder before dripping to the ground. The lift could also be explained with Bernoulli's equation (2-1). The air above the wing will travel with a greater speed than the air below, since the difference in altitude is negligible, there will be a higher pressure below the wing, generating lift. (Note, a general misconception is that the air travelling above the wing will meet up with the wind travelling below the wing at the same time and since the air above has travelled a greater distance it will have a higher velocity. The air above the wing will, actually, meet the trailing edge faster than the air below (due to geometry and the conservation of mass)).

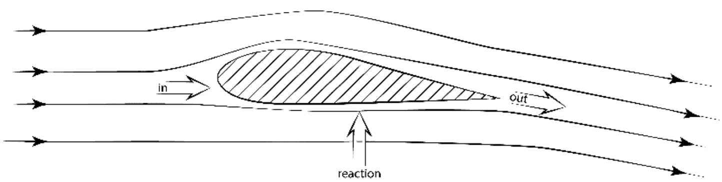


Figure 2-9 Lift power generated by an air foil

Drag is a phenomenon that could be described as resistance to the flow. It is a combination of pressure and friction forces (viscosity), hence a rough surface would create a larger drag. Simplified drag forces are forces acting parallel to the motion of the object or fluid and forces acting perpendicular are called *lift* forces.

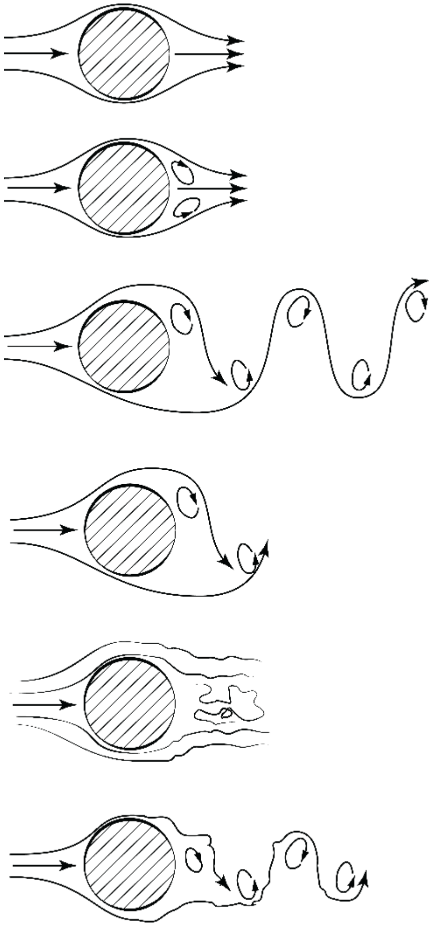
Most fluid flow that appears in nature is turbulent, like flow (wind) around a building. It is difficult to give a definition to turbulence (Davidson, 2018; Tennekes & Lumley, 1972), but some characteristics of turbulent wind is the randomness of the flow, that it is 3-dimensional, diffusive, dissipative (i.e. kinetic energy from larger eddies is transferred to smaller and smaller eddies until dissipates in the form of heat) and it occurs at large *Reynolds numbers* (Table 2.1).

Table 2.1 Reynolds number

Reynolds number (Re) is the ratio between inertia forces to viscous forces at a point in a fluid flow.	
$$Re = \frac{\rho v D}{\mu}$$	(2-2)
Where ρ s the density of the fluid (1.2 kg/m^3 for air), v is the velocity of the fluid, D "characteristic linear dimension" (for a rectangular body it is the with (m) normal to the flow) and μ is the dynamic viscosity of the fluid (18×10^6 Pa×s is typical for air). Thus, it is a dimensionless number. *Laminar flow* steady, parallel, non-turbulent flow occurs for flows with low Reynold's number. *Turbulent flow* have Reynolds numbers greater than ~3000 (Aynsley, 1999)	

Looking at the examples of flow around a cylinder, at different Reynolds numbers, in Figure 2-10, one can get an idea of how wind can behave around other objects such as buildings. Photos of the same and other phenomena could be found in *An Album of Fluid Motion* by Van Dyke (1982). However, as mentioned before, in an architectural scale Reynolds number tends to be high (because of the low viscosity of air and the large linear dimension) and turbulence occurs, which, per definition, makes it unpredictable. Typically wind flow around buildings will have a Reynolds number of the order of 10^5-10^8. Some effects of how wind behaves can be observed for example on snowy, windy days, where the light snowflakes will visualize the wind. Then, looking through a window, in a taller building, one can admire the snowflakes closest to the façade, moving upwards towards the sky again.

This introduction is aimed to give a general understanding of the behaviour of wind. However, the wind is always affected by its surroundings, including buildings. Hence the wind will be very difficult to determine, adding turbulence and it quickly gets complicated. R.M. Ansley even claims that, for wind flow around architecture, "intuitive guesses as to what an airflow pattern will be are usually wrong" (Aynsley, 1999, p. 73), architects should, therefore, test their designs with reliable techniques.



Re < 5

Unseparated streaming flow

5-15 < Re < 40

Vortices fixed in the wake

40 < Re < 150

A laminar vortex street

150 < Re < 3 × 10^5

Vortex street is turbulent

3 × 10^5 < Re < 3.5 × 10^6

Turbulent boundary layer, the wake is more narrow and disorganized.

3.5×10^6 < Re

A turbulent vortex street, which is narrower than in the case for 40 < Re < 150

Figure 2-10 Flow around a cylinder at different Reynolds number
(based on figure from (Blevins, 1990))

2.2.3 Wind Simulations methods

Computational fluid dynamics (CFD) simulations, could be divided into two approaches according to how the fluid flow (in this case airflow/wind) is described. With a Eulerian approach, the flow is studied from fixed coordinates, with the fluid flowing past these. Mesh-based simulation methods fall under this category. The Lagrangian approach instead tracks the fluid particles and their properties (like velocity and pressure), in this case, a mesh is not necessary. However, one problem with this method is that it is difficult to define a fluid particle. Smoothed-particle hydrodynamics (SPH) is one method using this approach and is discussed further in section 2.5.3.

Conventional CFD methods are based on the Eulerian approach, these are highly accurate but also tend to be slow in terms of computation time (Md Lokman Hosain &

Fdhila, 2015), this is especially true for simulations of flow around a highly flexible body, where the deformations of the body can be larger than the mesh cell-size. Thus, requiring re-meshing of the model to avoid overlaps in the mesh (this is further discussed in section 2.5.3). Methods such as the finite element method (FEM) have been widely applied to various areas of CFD and it plays an essential role in computational solid mechanics (CSM). The grid-based numerical methods divide a continuum domain into discrete subdomains where the nodes of the grid are connected to each other in a predefined manner by a topological map (mesh). Each subdomain (cell) and node, in the system, must have a predefined relationship to its surrounding elements. With a properly defined mesh, the governing equations can be converted into a set of algebraic equations with nodal unknowns for the field variables. These methods work well, for a lot of computational problems, however, there are complications with using a mesh. Firstly, with complicated geometries, generating a good mesh can be time-consuming, and requires substantial computing power. Secondly; dealing with problems with a free surface[2], deformable boundary, moving interface, and large deformations, becomes a problem when working with a predefined topology in a mesh.

In addition, there are simulation methods that use a combination of the mesh and particle simulation, also known as hybrid methods. A small overview of different simulation methods, focusing on non-conventional 'accelerated methods', can be found in (Md Lokman Hosain & Fdhila, 2015)

2.3 Lightweight structures in architecture

Lightweight structures in architecture is here defined as a structure that carries applied loads/fulfils its purpose while minimizing its dead load. Mike Schlaich gives 5 structural principles that can be followed to design lightweight structures (M. Schlaich, 2016).

- Work with appropriate (short) spans
- Avoid bending
- Chose materials with a good strength – weight ratio.
- Pre- and post-tension
- Double curvature i.e. carry loads through membrane stresses.

Heino Engel directly relates some of these principles to the geometrical form of a structure and classifies load-carrying structures based on how external loads are balanced by internal forces in the structure (Engel, 2013). The most efficient structures, in terms of material, are what Engels call, *form active* and the *vector active* structures that carry loads through pure tension and pure compression (i.e. no bending). Examples of form active structures are cable nets and gravity structures, and trusses are classified as vector active. Jörg and Mike Schlaich (n.d.) argue that these types of structures have never been more necessary than today, as we need to build more sustainable architecture. They claim that

[2] E.g. the highly deformable surface between water and air.

lightweight structures are sustainable, not only, from an ecological point of view, by reduction of material waste. The structures are also labour-intensive, and by adding value to time and craftmanship they are beneficial from a social perspective. Finally, from a cultural perspective, Schlaich and Schlaich claims that lightweight structures enrich architecture.

2.3.1 Spanning across or reaching the sky

One well-known example being, Antony Gaudi's hanging chain models, used to find the optimal geometry, in compression, for the church Sagrada Família, among others (Beukers & Hinte, 2005). Heinz Isler used wet or dry textile sheets, with the same approach when developing his thin shells, letting the textiles hang by their own weight. For example, dipping a piece of cloth, hung in four corners, in resin, letting it set, and then turn it upside-down making it a model of a compression structure (Chilton & Isler, 2000). Through explorations in models like this, he realised that he got a more stable structure by not removing the excess fabric around the edges when the resin had set, i.e. letting the edges be slightly folded (see illustration in Figure 2-11). One built example of this development in his shell structures can be seen in Figure 2-12.

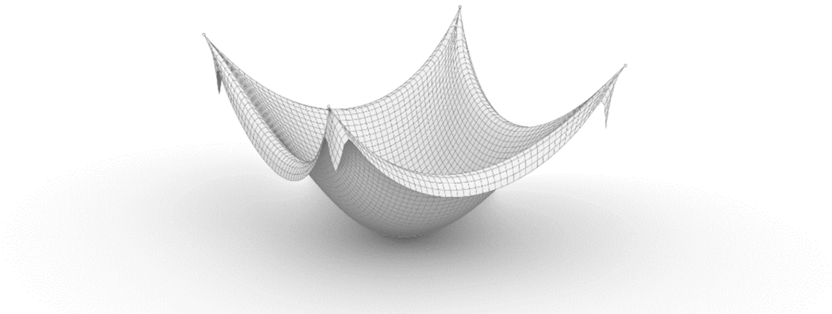


Figure 2-11 Illustration of Heinz Isler's fabric model, with the excess fabric around the edges.

Figure 2-12 Concrete shell roof (Isler shell) of the garden centre Wyss in Zuchwil, built 1962; Solothurn, Switzerland.

One of the most common types of pure tension structures is the suspension bridge. This efficient method of carrying loads has resulted in the longest bridges in the world, with the record for the longest bridge span at almost 2 km, currently held by Akashi-Kaikyo Bridge. Another type of pure tension structure is the tensile structures; surface structures consisting of pre-tensioned cable net, fabrics, or other types of membranes. These will be covered more in detail in section 2.3.2.

Tensegrity structures use a combination of tension cables and bars in compression to achieve a shape that is stable under external loads. It could be compared to a specialized truss, where some members are exchanged for prestressed cables. With this method slender and light structures can be achieved, the 30 m high sculpture, *Needle tower II,* by Snelson, being one example (Snelson & Heartney, 2013)(Figure 2-13). Examples of this method of carrying load trough specialised tension and compression members can also be found in nature, for instance in our bodies that have muscles and tendons that can distribute tension and bones that handle the compression forces (Beukers & Hinte, 2005).

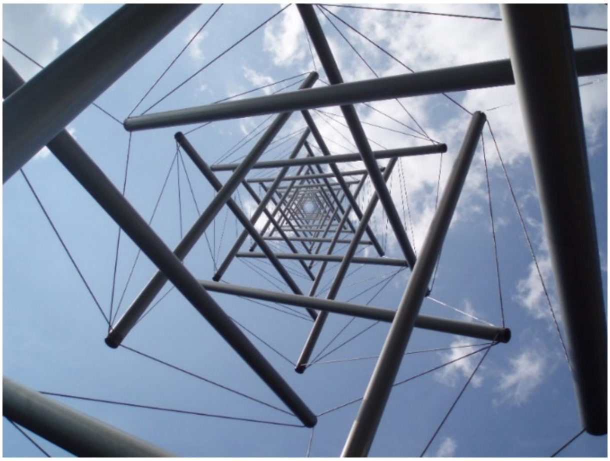


Figure 2-13 Needle tower II, 1969, a 30 m high (6x6 m in plan) tensegrity tower in aluminium and stainless steel, by Kenneth Snelson.

The term T*ensegrity* was invented by Buckminster Fuller in his patent form 1962 (Buckminster, 1962). However, the artist Kenneth Snelson is today, generally regarded as the inventor of the tensegrity structures, with his *X-piece* from 1948 (Tibert, 2002), even though Fuller beat Snelson to applying for a patent[3]. In his paper, The Art of Tensegrity Snelson compares tensegrity structures to textiles weaves, he even describes 'weaving as "the mother of tensegrity"' (Snelson, 2012, p. 77). He explains that the same pattern as can be found in the basic tensegrity cells (i.e. rotated polygons), can be found in the two fundamental weaves; the two-way plain weave and the three-way

[3] Kenneth Snelson also applied for a patent, around the same time as Fuller, for 'Discontinuous Compression, Continuous Tension Structures" in 1960 (issued five years later) (Snelson, 2012)

triangle/hexagon weave. This connection between textiles and tensegrity is further explored by Borgny and Wallander in their MSc thesis Textile Informed Structures - How to Braid a Roof Translating the logic of textile structure into the scale of architecture (Borgny & Wallander, 2019) and in (Wallander et al., 2019). More details about the prestress in tensegrity structures, and examples can be found in (Sehlström, 2019).

2.3.2 Carry load through pure tension or pure compression

To bridge a gap with as little material as possible, the most material-efficient solution would be to use a cable to span across. However, as the weight of the cable is small compared to applied live loads, the shape of the structure will change more than acceptable, if used as a bridge for example. Therefore, different solutions to get a stable shape have been developed, the most common being to add a beam, under the cable., i.e. create a suspension bridge (Figure 2-14). The beam will distribute a point load, through bending action, making the change in shape of the cable less dramatic. In addition, the deadload of the beam will likely be larger than the predicted live loads. It is more efficient to carry loads through tension (though not always practical) since there is no risk for buckling. Structural members in compression need to be designed to counteract this risk. This is done by increasing the stiffness, e.g. increasing the size of the cross-section, or through other design aspects of the member, see (Olsson, 2005) and (Engel, 2013) for further information and examples. Hence a tie can be slender while a pillar needs a larger cross-section to carry the same load.

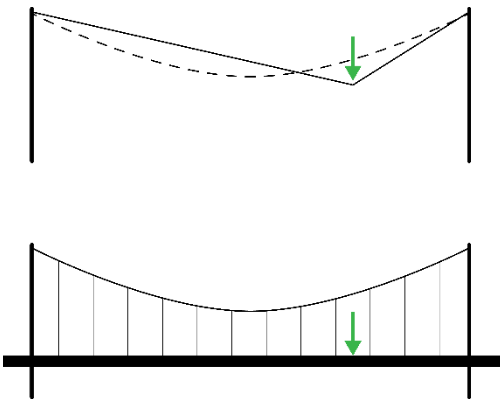


Figure 2-14 A cable can efficiently carry loads but will deform heavily under applied loads. One method to stabilize the shape is to add a beam and connect that to the cable.

Lightweight structures keep their shape through their designed geometry (to minimize bending), in combination with pretension. Examples of geometries can be found in the diagram created by Jörg and Mike Schlaich, in Figure 2-15, where the inner circle shows examples of methods to span across. Structures above the mirror line, in the diagram, are carrying load through compression and those below through tension. It can be noted that the geometries are, mirror images, which has been used throughout history, when designing shell structures and arches. In fact, Robert Hooke wrote about the hanging chain being a mirror image of a standing arch, already in 1675 (Heyman, 1999)

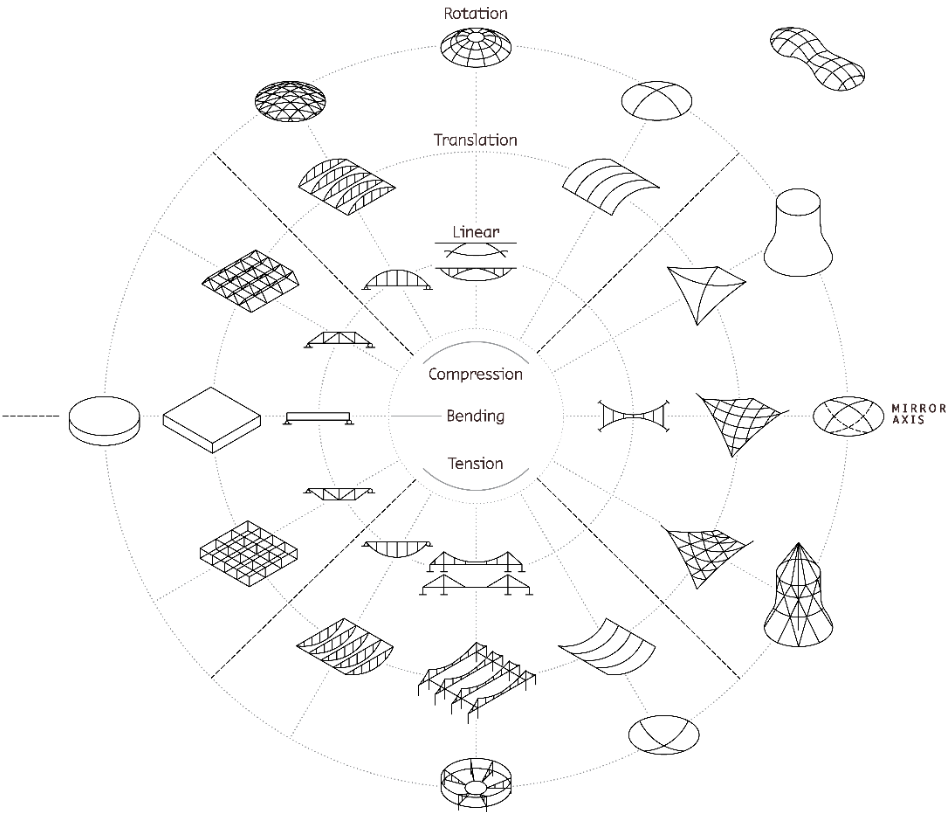


Figure 2-15 Diagram sorting lightweight structures according to their geometry and purpose. Source of the diagram: Mike Schlaich (J. Schlaich & Schlaich, n.d.).

2.3.3 Simulating lightweight structures

To design as light structure as possible one of two techniques is often used; form finding (also called shape optimization) or topology optimization. The first method aims to change the geometry of a structure so that all nodes in the system are in equilibrium with an applied load case. Usually, a structure with no, or as little bending as possible is a goal. For form finding of tension structures, the load is a fictional tension in all (inner) links. With gravity structures, the goal is the optimal shape to carry its self-weight. Heinz Isler did such form finding with physical models (Chilton & Isler, 2000) and Frei Otto for both tension and compression structures (Otto et al., 2017). A common way of simulating this is through dynamic relaxation (DR), a calculation method developed specifically for computer calculation, by A. S. Day (1965). In short, form finding with DR is an iterative process starting with an unbalanced structure, where the out of balance forces are translated into moving-distances for nodal points in the model. Through Newton's second law of motion $\boldsymbol{F} = m\boldsymbol{a}$ (force equals mass multiplied by acceleration), where, in this case, both the force and the mass are known, moving-distances can be calculated from the acceleration by introducing fictional timesteps. This method will be explained in more detail for tension structures in 2.4.3. Other methods for form finding are also possible, such as the force density method (Schek, 1974) and (Williams, 1990a) is using a stress function for the form finding of vaults and sails.

As the name implies, topology optimization aims to find the optimal topology, according to a set of criteria, e.g. applied loads and boundary conditions. This could be done by adding or removing parts of the design domain. Thus, voids could, for example, be created in a beam or plate and members could be added or removed in a truss. (Sehlström, 2013). A good description of structural optimization, in connection to geometry and topology, is given by (Baker et al., 2015), showing both classical design methods, such as graphic statics, as well as digital algorithms.

2.4 Tensile structures

At the intersection of textile architecture and lightweight structures we find, the tensile structures i.e. surface structures designed to only carry loads in tension. These structures tick off several of Mike Schlaich's points, listed in 2.3: no bending (as textiles, membranes and cable nets have little bending stiffness), post-tension, high tensile strength, and double curvature. They are specialized textile structures that take advantage of the material's high tensile strength. In this section, some examples will be given as well as a description of the geometry and a common way of simulating the structures.

2.4.1 Architecture that utilizes textiles' strength and lightness

Tensile textile architecture is a big field for textiles within architecture. In papers and books "textile architecture" or "fabric architecture" often seem to equal tensile architecture (Koch et al., 2004; Llorens, 2015), especially within the field of structural engineering. The quote: 'Architectural fabric structures – also referred to as tensile membrane structures, textile buildings, or fabric roofs, to mention just a few terms- come in a variety of shapes and sizes…' (Armijos, 2008, p. 11), suggests that all 3 of the terms, above are synonymous, thus not acknowledging the other types of textile architecture, that are mentioned in section 2.1.

For arenas, of all kinds, membrane structures have become a popular option, as the strength and lightness of textiles allows for the coverage of large areas without intermediate supports. A good example is the O2 arena (also known as the Millennium dome) in London (Figure 2-16). The umbrellas at the Medina Haram Piazza, where 250 umbrellas give shade to millions of pilgrims every year, exemplifies how the flexibility (as well as the strength and lightness) of textiles can be utilized. These are tensile structures that can be folded so that the umbrellas turn into narrow columns when not needed.

As tensioned fabric structures start to become more intricate parts of a variety of building types the demands on the material gets more and more complex, in case of energy, sound absorption, translucency, etc. At Suvarnabhumi, Bangkok international airport finished 2006 (Figure 2-17), a multiple layer system was used to achieve a better absorption of sound coming from both the interior and the airplanes on the outside (John Morris Dixon, 2007).

Figure 2-16 Millennium dome (O2 Arena), in London. A large textile dome.

Figure 2-17 The structure of the terminals at Suvarnabhumi, Bangkok international airport, uses textiles in a multiple layer system.

While todays tensile structures are primarily built using woven textiles closely followed by ETFE-membranes and cable nets, current research is also targeted towards using knitted textiles, often together with an actively bent structure (Ahlquist, 2015, 2016; Ahlquist et al., 2017; La Magna et al., 2018; Lienhard et al., 2013; Tamke et al., 2015; Thomsen et al., 2015).

2.4.2 The shape of tensile structures

Tensile structures need to have an anticlastic shape (the exception being pneumatic structures), so that the double curvature can ensure that all loads could be carried through tension. Examples of common shapes for tensile structures can be seen in Figure 2-18. The structural optimal shape for tensile membrane structure is the minimal surface, i.e. the shape and size that a soapfilm would take, with given boundary conditions. This shape could then be modified through pre-tensioning. Therefore, soapfilm models are useful for finding the shape of these structures (Figure 2-19) (though, they are difficult to keep for a longer time).

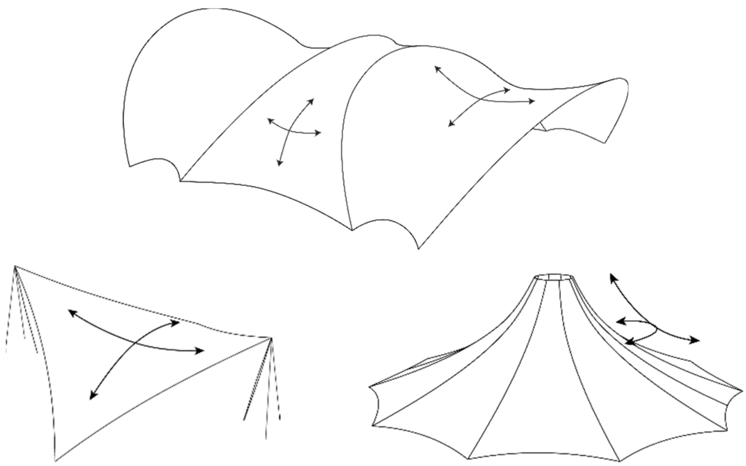


Figure 2-18 Anticlastic shapes of tensile structures

Figure 2-19 Image of a soapfilm model produced during a workshop, held at Chalmers University of technology 2018, by Emil Adiels, Tim Finlay, Isak Näslund, Puria Safari and Chris Williams

2.4.3 Simulating tensile structures

In most cases, the shape for tensile structures is not given by any obvious mathematical function. It needs to be found through a form finding process (Lewis, 2003). This could be done with physical models, soapfilm models being one option, which architect and engineer Frei Otto has shown several good examples of (Otto et al., 2017; Otto & Rasch, 2006). Today, form finding is generally done using computer simulations, where the Dynamic Relaxation (DR) method by A.S. Day (1965) is one of the more commonly adopted methods (Koch et al., 2004). It is also the method used for the simulations in the appended paper (Henrysson et al., 2016) summarised in section 4.3, and in (Henrysson, 2012) (written by the author). In short, the structural model is discretised, and mass lumped to a set of nodes. If it is a cable net, the nodes are usually set to the intersection between the cables. For a textile structure, the weave is simplified to a 2D material/surface with zero thickness. (On an architectural scale the thickness of the textile is negligible.) The surface is then divided into a triangular mesh, which allows for different properties in the warp and weft directions (Figure 2-20). The forces on each node (which might generate a moving distance) is calculated through first iterating through all mesh faces (if it is a surface structure), forces from the surface is added to the links/edges, then all links in the system is looped and, if they are representing a cable, cable force is added. These forces are then the ones acting on the nodes in the system (Figure 2-21). New positions for the nodes are calculated and the and another iteration commences. These steps are summarised in the run-loops in Table 2.2, used for the simulations in (Henrysson, 2012; Henrysson et al., 2016). Note that the process for form-finding and analysis of these structures are slightly different. Barnes (1999) are describing the details and mathematics, for this process, further.

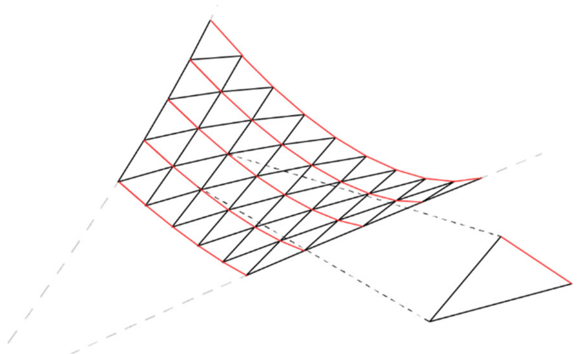


Figure 2-20 Illustration of the mesh and triangles, where the red lines are representing the warp direction. Calculations are carried out, separately, for each triangle in the mesh.

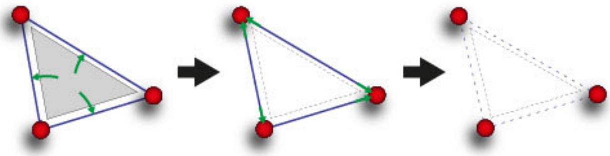


Figure 2-21 Illustrating the algorithm. Step 1: the tension from the membrane is added on to the links, step 2: the forces in the links are added to the nodes and with that all the information needed to calculate new positions for the nodes.

Table 2.2 Run-loops for the steps of form-finding and analysis of tensile structures, used in (Henrysson, 2012).

Form-finding	**Analysis**
Set up base geometry (mesh) and assign material properties. **Run loop** • Set all nodal and link forces to zero • Calculate the stiffness for each link (for the stress-controlled membrane this value will change as the geometry evolves.) • Calculate forces in control strings (links that coincide with the warp direction). • Calculate dynamic masses. • Transfer the assigned warp and weft prestress to the links. • Calculate forces in the cables (elastic). • Transfer the forces from the links onto the nodes. • Calculate the resulting accelerations, velocities and displacements. • Update the locations for the nodes	Change all links to be elastically controlled (with the form-found geometry as the initial one) **Run loop** • Set all nodal and link forces to zero • Apply loads (gravity and any other load given by the user). • Calculate the stiffness for each link (For membrane both elastic and geometric stiffness. • Calculate dynamic masses. • Calculate the total membrane stresses (pretension plus direct and shear stresses). • Convert membrane stresses to link forces. • Calculate forces in the cables (elastic). • Transfer the forces from the links onto the nodes. • Calculate the resulting accelerations, velocities and displacements. • Update the locations for the nodes

The governing load case for tensile structures is usually wind loads, which for some structures may be taken from guidelines like the Eurocodes. However, for more complex structures wind-tunnel tests or perhaps computational fluid dynamics (CFD) simulations are needed. Although the turbulent flows around the building structure in combination with that the wind might cause movement in the textile makes simulations very complex. This will be further discussed in section 2.5.3.

2.5 Wind in combination with Textiles

> '…When you encounter one of my sculptures this, monumental softness moving in the wind, it reminds us that the wind is already there. It is as if the wind is the choreographer. And I love that I have no control of it!' (Janet Echelman, 2017)

In this section we will look closer at wind interacting with textiles, focusing mainly on loose textiles free to move. The light textile material picks up the random movement in the wind creating structures in motion with soft, billowing shapes that adjust to the force in the wind. Inspiration has here mainly been taken from examples in fields outside the field of architecture since architectural examples are scarce.

2.5.1 Textile and wind in architecture

In the field of architecture examples of exterior textiles, free to move in the wind, are rare. One example is the fabric façade on a studio house, in Almere, The Netherlands, by architects CC-Studio, Studio TX, and Rob Veening, which is built up by PTFE-coated fiberglass fabric (from residual waste) cut and placed as overlapping shingles, free to move in the wind. The Book House Pavilion, by Olga Sanina + Marcelo Dantas architects and COS Space by Snarkitecture are also examples of architecture using textiles free to move. At the border between architecture and art, we find Janet Echeman's knotted net sculptures, taking demand of the in-between space between buildings. Common for the examples above is that, even though the structures are free to move, the motion is not designed but rather a welcome effect.

2.5.2 Using textiles to gain from the wind

Stiffness of a fabric perpendicular to its plane is created mainly through tension "in-plane", with bending capacity secondary. But, the tension in the fabric also depends upon the wind loading, and for stable structures the tension increases with wind speed. In addition, the change in shape of a fabric structure (due to wind loads) will result in a change in pressure and thus a change in the aerodynamic stiffness. This stiffness is often negative leading to a reduction in stiffness of the structure.

The way a fabric structure moves in the wind is not so much an oscillation as it is waves travelling across the fabric (Williams, 1990b). The speed of the smaller waves, the ripples, traveling along fabric moving in the wind is dependent on both the wavelength and the tension in the fabric, whereas larger waves are more dependent on the mass of moving air. The speed of the ripples is proportional to the square root of the tension per unit width divided by the wavelength. Thus, shorter wavelength waves travel with a higher speed and overtake longer wavelength waves. In the case of a flag the tension is at a maximum at the mast and drops to zero at the trailing edge. This means that the wave speed drops as waves leave the mast resulting in increased wavelength, further reducing the wave speed. The tension in a flag is due to viscous shear stress in the air, and the inertia of the flag itself as it flaps. Shelley and Zhang(2011) contains a discussion of some of these aspects.

The mass of air moving with a fabric will usually greatly exceed that of the fabric itself[4], which means that it is possible that in a soft fabric the wavelength is controlled more by the wind vortex scales.

Few examples in architecture uses textiles to benefit from the wind. However, examples of successful parings of textiles and wind can be found in other fields. Sails and kites being two of them. Here, the textile is used to harvest the force in the wind. The traditional kite and the western sailboat use struts/mast and boom to stretch out the textile in order to catch as much wind as possible. The force can then be adjusted by the steering of the kite/boat and the angle of the sail. For kites used in kitesurfing (Figure 2-22) the structure that holds the textile is air-beams/bladders, but the general principle is the same as for the sails and kites mentioned above. An interesting sail-type is found on the Asian Junk which' sail adapts its wind-catching area in relation to how large the wind force is (Gordon, 1978) (Figure 2-23). This way the generated speed is kept more constant but more importantly the risk of the sail ripping or the boat getting turned over by large wind forces are greatly reduced.

Figure 2-22 The kite is harvesting the power in the wind to give speed to the surfer.

The flexibility of the textile material forces it to adapt to any force applied to it. In a dance performance the dances could be seen as the structure that textiles are attached to. One artist that took the performance of the textiles in the dance to a new level was dancer Loïe Fuller (active in the end of the 19th and beginning of the 20th century) (Figure 2-20). 'She became the moving vortex of billowing luminous silk. Movement of the body served only to set the silk in motion, and all movement activated the draperies' (Sommer, 1975, p. 3). More recently, Jody Sperling (inspired by Fuller) uses voluminous textiles to enhance her performances. Taking this one step further, the artist Daniel Wurtzel creates similar affects, without the dancer, with his art installations (e.g. magic carpet, Pas de Deux and Air Fountain). In his installations it is moving air that becomes the "body" that

[4] Density of air is 1.2 kg/m^3, and a coated fabric can weigh 0.3 kg/m^2 (Koch et al., 2004).

directs the light textiles. The phenomena of textiles set in motion by wind, is also explored in fashion, where designer Yoshiki Hishinuma's "Kite Clothes" and "Air Clothes", from the 80's, are good examples. τ_{xy}

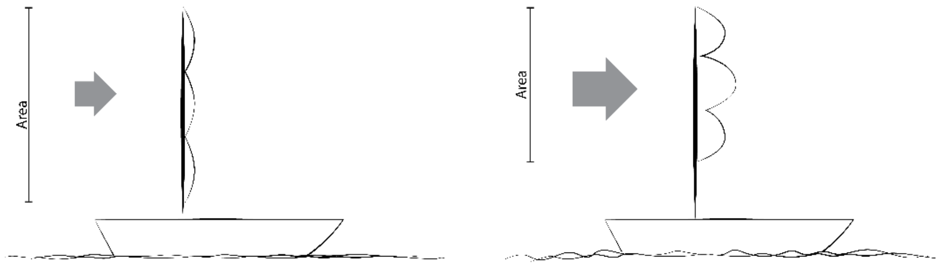


Figure 2-23 Asian Junk adapts the sail area according to the force from the wind.

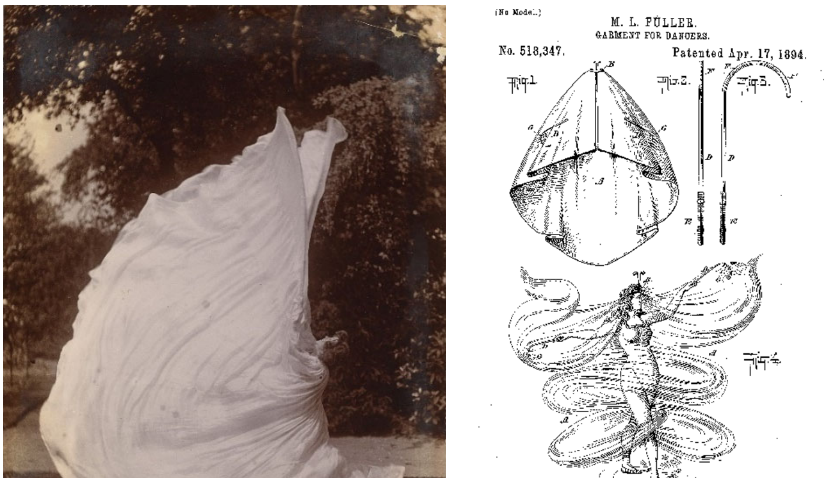


Figure 2-24 Left: Dancer Loie Fuller. Right: Patent by Fuller for 'garment for dancers' (Marie Louise Fuller, 1894)

For this thesis the relationship between textile, wind and the dancer have been further researched. The dancer Arika Yamada, explored the movement in the textile and air and the relationship between her body and the textile, Figure 2-25. She expressed it as 'the textile became almost as a partner in dance'. The picture below shows how Yamada's body becomes the structure that together with the wind (from a fan) directs the motion of the textile. The light and the translucency of the weave further enhance the effects in the motion. In a small workshop/open ended exploration, first year architecture students got to design space, with textile and wind. One of the resulting structures was the "kinetic sculpture" in Figure 2-26, here the body that carries the structure is a metal frame, and the shape and movement is created with moving air from a fan.

In their essence, these examples are all variations of textiles held up by some structure or body. Similarly, the building could also be regarded as a body that holds and directs the textile movement in combination with wind.

Figure 2-25 Dancer Arika Yamada, exploring textile motion through dance.

Figure 2-26 "Kinetic textile sculpture", created by first year architecture students 2019.

2.5.3 Simulating wind and textiles

For textile architecture, wind is usually the governing load case, yet it is difficult to calculate the wind around these geometrically complex shapes. Analysis is further complicated by the fact that the wind will cause the textile to deflect and move with the wind. For strong winds this is true also for heavily prestressed structures. Thereby the analysis is a, so called, fluid-structure-interaction (FSI) problem, meaning that it is necessary to track both the movement in the fluid around the structure but also the movement in the structure itself, and the forces that they exert on each other. This is a challenging area for CFD (computational fluid dynamics), especially when large deformations occur. As in the case of textiles. Methods for simulating FSI problems could be divided into two categories; the partitioned and the monolithic approach. For most engineering problems, the partitioned approach seems to be prevailing, here a Eulerian-Lagrangian method are used in classic mesh-based simulations. (A Eulerian approach means that the flow is calculated at fixed points, e.g. mesh divisions, thus looking at the flow through these stationary points/areas. Whereas the Lagrangian approach calculates the fluid (or solid) properties of an element at different times and positions in the model.) The fluid flow is calculated through a Eulerian approach and the “solid” structure is calculated separately with a Lagrangian approach. The main drawback with this approach is the necessity and difficulties associated with information exchange between the two systems. The large deformation of the two meshes require substantial CPU power. For the monolithic approach the forces and movements of the fluid and the solid is calculated simultaneously. This could be done with, for example an SPH-SPH approach or a SPH-FEM approach (i.e. SPH for the fluid and either SPH or FEM for the solid). SPH stands for Smoothed Particle Hydrodynamics, which is one of the most common mesh free CFD methods (Shadloo et al., 2016), it can also be regarded as the oldest modern mesh free method and is very powerful for CFD problems governed by the Navier-Stokes equations (see Table 2.3 for more information About SPH). Chris Williams have created an illustrative example of a SPH-simulation, for wind interacting with a flag (2D) (Figure 2-27) where the particles that have collided with the flag is shown in red or blue, depending on their rotation (other particles are not visualised). A more thorough description and review of the SPH method could be found in (Liu & Liu, 2010).

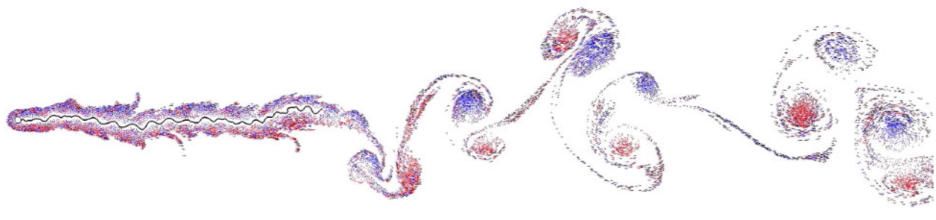


Figure 2-27 Particle simulation of fluid flow interacting with a flag, in 2D (a cross-section). Simulation created by Chris Williams, using a SPH approach.

Given the higher speed of mesh-free methods, such as SPH, and the ability to handle large deformation such as cloth moving in wind, it is used in the field of computer animation. However, it does not seem to be widely used for fluid engineering. A comparison between the, in fluid dynamics more common, finite volume method (FVM) (using the Eulerian-Lagrangian approach) and the SPH method, for industrial heat transfer problems was carried out in (M.L. Hosain et al., 2019), showing slight differences between the results of the two analysis methods, however, the study claim that SPH has great potentials to be an alternative to FVM.

Table 2.3 Summery of the smoothed Particle Hydrodynamics (SPH) simulation method

Smoothed Particle Hydrodynamics (SPH):
The state of a system is represented by a set of particles, which possess material properties and interact with each other within a range controlled by a smoothing function. Advantages: • It is a particle method of Lagrangian nature and can obtain the time history of the material. • Free surfaces, material interactions, and moving boundaries can be traced naturally within the process. • As the material is modelled by "free" particles it allows for a straightforward handling of large deformations, as well as rips/fractures, since the relationship between the particles are updated throughout the process. Thus, a particle can be attached to one particle, in the beginning, and during the simulation de-attach and reattach to another particle. • The method is relatively easy to numerically implement and to use for 3D-models. Challenges: For fluid and solid mechanics there are, however, challenges involving accuracy and stability of the SPH simulations (more information about the limitations can be found in (Shadloo et al., 2016). Over the past years different modifications have been tried to improve this. One of these is the finite particle method (FPM), which uses a set of basis functions to approximate field variables at a set of arbitrarily distributed particles (Liu & Liu, 2010).

One of the few papers that study the dynamic behaviour textile structures in wind is (Alexander Michalski et al., 2011). Where they did computer wind simulations as well as validation with a full-scale 29 m umbrella structure. For this study they use a partitioned, Eulerian-Lagrangian approach, to solve the system (A. Michalski et al., 2009). Other papers has also described computer fluid simulations and analysis of tensile, flexible structures, like (Elnokaly, 2014; Glück et al., 2001) and the usefulness of these simulations. Fluids interacting with a flexible material is a common topic, in research about computational fluid dynamics. However, for both FSI research focusing on tensile structures and on, so called, flexible material that have more bending stiffness, the movement of the analysed structures are relatively controlled, compared to a piece of cloth free to move, flap and intertwine in the wind. Which might be one reason for why mesh-based analyses seem to be more favoured, also for FSI.

2.6 Kinetic architecture

> 'the problem with buildings is that they look desperately static'
> (Latour & Yaneva, 2008, p. 80)

In the essay "Give me a gun and I will make all buildings move: An ANT's view of architecture" Latour and Yaneva (2008) points out that buildings are never static, with time they change, age and get transformed by its users inside and outside. They do, however, look static. In this thesis *kinetic* is referring to a shorter time, where you can visually observe the change by only looking at a building. Furthermore, kinetic architecture is defined as buildings or structures where the movement is seen as an important design element of the building envelope. The movement itself can be divided into two types (1) motion used to get from A to B and (2) the motion is a goal in itself. Contrary to movement such as e.g. elevators, escalators and doors, used for transportation and "non-integrated" external and internal shading systems etc. (belonging to the first category) the focus, in this section, is on the second type of movement and the interface between lightweight structures and wind, which means that emphasis is on wind driven movement.

2.6.1 A variation of drivers for motion

By creating building elements that move, a new template of design possibilities is added, with extended abilities to adapt to the surroundings. Santina Di Salvo (2018) gives a wide description of kinetic facades that also includes the aesthetic and communicative appearance of the building, in addition to energy efficiency, which otherwise seem to be the main drive for kinetic facades. (Barozzi et al., 2016) gives examples of how kinetic facades has been used for solar shading as well as lifting the need to design more intelligent systems, to reduce buildings energy demand. Flexible, light and translucent material such as textiles and membranes, especially smart textiles, are materials that work well with the kinetic concept (Kirstein, 2013; Monticelli, 2015). Biomimicry[5] is an often used as a design method (Badarnah, 2017; Korner et al., 2016).

Most kinetic buildings use mechanics driven by electric motors. An early example of this is the façade of Arab Institute in Paris, from 1987 by architect Jean Nouvel (Figure 2-28). Here the intelligent metallic brise soleil, can open and close to control the amount of sunlight that is let into the building. A more recent example, a kinetic façade used for controlling the sun radiation, is the Al Bahar Towers in Abu Dhabi, from 2012, by Aedas (Figure 2-29). The façade of the Thematic Pavilion for Expo 2012 is a good example of where biomimetic research and design where used to create a kinetic structure (Knippers

[5] Drawing inspiration from nature and mimicking the behaviour of plants and animals in architectural design.

et al., 2012). The façade has louvers that are elastically bent to open and close, a movement that were inspired by the opening and closing of flowers.

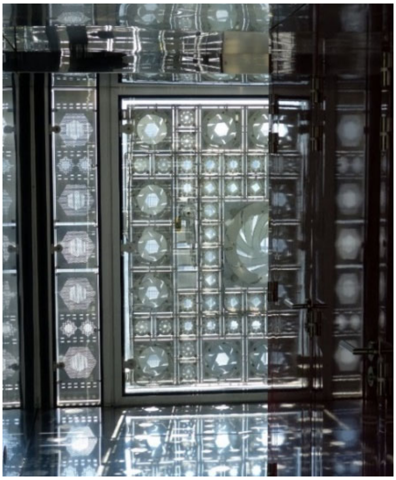


Figure 2-28 Interior detail of Arab Institute, Paris, 1987 – Jean Nouvel

"Passively" driven kinetic structures can be found outside the field of traditional architecture. Passively here means motion caused by forces in nature, without the help of electric installation. Like the façade *Wind Veil*, one out of many similar structures by the artist Ned Kahn, where several small, hinged aluminium plates are free to move in the wind. Generating an effect that mimics a textile flowing in the wind or a waterfall. The architectural research installation, Bloom, is using thermobimetals, to generate a motion driven by temperature variations (Fortmeyer & Linn, 2014). Another example is the wooden research pavilion, HygroSkin, by Achim Menges Architect, Oliver David Krieg, Steffen Reichert, which has elements that respond to and opens and closes according to the relative humidity (Menges & Reichert, 2015).

Figure 2-29 Kinetic solar shading; Al Bahar Towers, Abu Dhabi, 2012 – Aedas

2.6.2 Creating movement

A mechanical movement in space could be defined through two primary forms of motion: translation and rotation, see Figure 2-30, (elastic materials could also stretch (i.e. scale movement)). Both categories have degrees of freedom (DOF) related to geometrical constraints in the three coordinate-axis (x, y, z). A maximum of six DOFs can be achieved if a body is free to translate and rotate in any direction. By locking one or several DOFs, different typologies of movement could be defined. A mechanical rotation could be a swivel (restricted rotation), a revolving (free rotation) and a flap ("off-centre" rotation) (Schumacher et al., 2010). Translations could be parallel to a surface or perpendicular and combining rotation and translation you get a fold. With flexible and elastic materials further types of movements are added, such as roll, bend and flutter. Illustrative tables with the above categories of movements can be found in (Schumacher et al., 2010).

When designing kinetic structures, the speed of the movement is also important for the impression of the final result. As an example, Wind Veil (described in the previous section), is constructed with several small plates having 1 DOF. The force from the wind make them flap i.e. rotate around one axis, but translations are not possible. The plates can move with a relatively high speed, but still perceptible to the eye.

Reviews on how these principles have been and could be applied to facades for solar shading could be found in (Al-Masrani & Al-Obaidi, 2019; Fiorito et al., 2016)

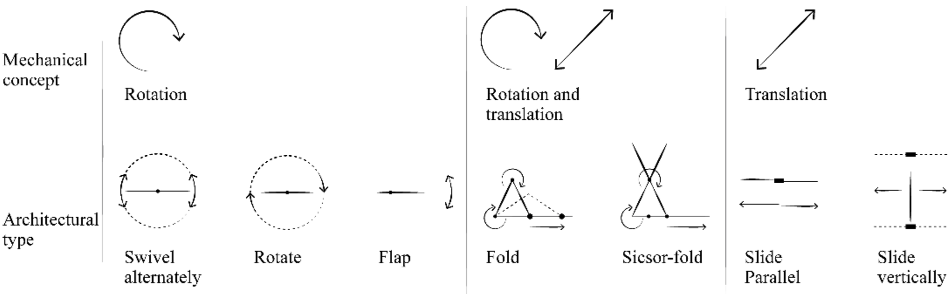


Figure 2-30 Mechanical movements in space through rotation and translation (illustration based on figure in (Schumacher et al., 2010))

2.6.3 Simulating movement

The simulation of movement of interconnected systems of rigid or flexible bodies, i.e. multibody dynamics is based on classical and analytical mechanics (Arnold & Schiehlen, 2009; Schiehlen, 2007). An overview of the developments of this field is given by Eberhard and Schiehlen (2006). As well as being useful in an architectural context these types of simulations cover a wide range of purposes; large deformations, contact and impact problems, machines and mechanisms, vehicle dynamics and biomechanics to name a few.

2.7 Textile architecture informed by wind

This chapter is now landing in the smaller field, defined by the intersection between the three fields from which it took its depart: *Textiles, Wind informed,* and *Lightweight.* This intersection defines the title of this thesis: *Textile architecture informed by wind* and it is in this area that the initially posed research questions should be asked:

- How can the field textile architecture informed by wind be systematically described to clarify central aspects of textiles and wind in architecture, and through them act as inspiration for new applications?
- How can an architectural design process, for stiff and/or flexible textiles, be supported by digital (numerical) tools, appropriate representations, and explorative use of prototypes?

In this chapter the relatively unexplored field of flexible textile architecture designed to move in the wind has systematically been described through defining three core elements of the field: T*extiles, Wind informed,* and *Lightweight.* It has also looked closer at the intersection between these elements two-by-two: *Tensile structures, Wind in combination* with Textiles*,* and *Kinetic architecture*. In all six of the above sub-fields examples have been given, characteristic phenomena explored and simulation techniques have been described.

Central aspects of the studied field are:

- The composition of the textile material. That it has an almost negligible thickness, consists of fibres or threads that interlock and has low bending stiffness.
- The flow pattern of the wind and, especially, the turbulence that occurs around buildings. That an efficient way to create a comfortable wind environment is to filter the wind through a porous material (like most textiles) and potentially absorb the wind energy.
- The geometry of light wight structure and material efficiency in carrying load through tension. That lightweight structures, including tensile structures, are usually heavily prestressed to not deform under applied loads, such as wind.
- The composition of boundaries of kinetic structures. That the motion of a flexible structure is controlled by restricting some of its possible mechanical actions.
- The interaction between the textile material and a moving body or moving air. That a dancer, in voluminous light clothing, is, in essence, a structure/body that holds and directs the movement of the textile through the air.

This list of central aspects of the research field is both a summary but could also be used to formulate new research experiments, which will be discussed further in chapter 0.

Regarding the digital numerical tools for the simulation of loose textiles on an architectural scale the overview in this chapter has shown that:

- Different textiles require different material models, e.g. a woven textile behaves does not react to external forces in the same way as a knitted textile, thus requiring specific material representations.
- A mesh-free simulation is preferable for the conceptual design of architectural structures with loose textiles moving in the wind since the more traditional mesh-based wind simulation methods are unpractical for such large deformations.

In the following chapter, the methods used to answer the research questions will be presented.

3 Research design

This section consists of a reflection around chosen research methods and the role they play in knowledge making. Followed by a description of how these methods have been implemented to generate data for the research.

Research could be defined as a 'systematic enquiry directed toward the creation of knowledge' (James Snyder, 1984, as cited by Wang & Groat, 2013, p. 26). This definition does not exclusively mean that the sources for the enquiry are literature or written knowledge, nor does it have to generate a quantitative (see Table 3.1) knowledge as output. A main purpose of the research is to give a better understanding of the phenomenon that governs the interactive behaviour between textiles and wind, and effects thereof. As well as to give a suggestion for a systematic use of prototypes in an exploratory design process. This governed the choice of research methods. Predominantly, qualitative approach (Table 3.1) to the research is used. Accordingly, the evaluation and the results are not claiming to be an absolute truth, but depending on the context, application, and person interpreting the results. The goal is to explore the field of research and show possible potentials with combining flexible textiles with wind. This approach is, however, mixed with some quantitative investigations. Therefore the general approach could also be said to be a mixed methods approach (Creswell, 2014). Thus, the research relies on two cultures of knowledge building: the architect's, and the engineer's. Where the latter is a more "traditional, scientific" (i.e. quantitative) culture with development of mathematical models for physical phenomena and application of mathematical algorithms used for verification of hypothesises and design. Whereas the architect culture does not rely on any single research approach. This research applies the architectural approach 'the method of design inquiry' which Richard Foqué explains as:

> 'The essence of the design inquiry […] aims to develop in parallel as many hypotheses as possible, not on the basis of exploratory models but of exploring ones, models with probing capacity. Testing seeks to identify the most desirable result. It is at the same time an optimizing, judging, and subjective activity.' (Foqué, 2010, p. 42)

The main methodology for the research, for this thesis, is research by design. A concept that is explained by (Foqué, 2010) and put into context by (Nilsson & Dunin-Woyseth, 2011, 2012). Design is used as a method to generate knowledge. Where design installations/structures/prototypes play a vital role in the knowledge-making. They are regarded as a way to intervene with, explore, and research a place, material, or phenomenon and the work is carried out in an iterative manner. Putting myself and others in scenarios that trigger thoughts and allowing curiosity to run free, documenting these through photos, film, and notes describing the phenomena.

Table 3.1 Key differences between quantitative and qualitative approaches. Adapted from Architectural research methods (Second Edition) by Wang, D., & Groat, L. N., 2013, p. 71, John Wiley & Sons, Incorporated.

Question	Quantitative	Qualitative
What is the nature of reality?	Reality is objective and singular, apart from the researcher.	Reality is subjective and multiple as seen by participants in a study.
What is the researcher's relationship to the research?	Researcher is independent from the research itself.	Researcher interacts with the research.
What is the process of research?	Deductive process: cause and effect.	Inductive process: Mutual simultaneous shaping of factors.

Contrary to the more traditional engineering/scientific research that uses a deductive reasoning to get to the results or understanding, this research is generally based on an abductive reasoning which Wang and Groat (2013) describes through an "equation":

WHAT	+	HOW	leads to	VALUE
(thing)		(working principle)		(aspired)

Abduction reasoning is either trying to find the thing ("what") that leads to the desired value with a known working principle or could be that both the "what" and the "how" is unknown".

3.1 Applied research methods

In section 1.1 of this thesis two research questions were defined:

- How can the field textile architecture and wind be systematically described to clarify central aspects of textiles and wind in architecture and through them act as inspiration for new applications?
- How can an architectural design process, for stiff and/or flexible textiles, be supported by digital (numerical) tools, appropriate representations, and explorative use of prototypes?

The tools used to break down and understand these questions are divided into two categories: a literature study, and design inquiries. Where a literature study aims to answer the first question. To answer the second question the method of design inquiries (Foqué, 2010) have been used. Exploring questions like: what are the main aspects of the complex phenomena of textiles moving in the wind? And how can key elements and/or features be extracted and communicated? Furthermore, how textiles can be represented and simulated in a computer model has been examined. As well as, how the boundary conditions affect the model and what other components govern the simulations and thus, the simulated phenomena?

3.1.1 Literature study

With the aim to frame the research and put the explorations of the textile material and wind into context, a literature study was carried out. This study could be divided into two parts:

One where key aspects and examples of the fields were studied and summarized, these have been chosen based on previous knowledge, and advice from people in the research group and from people who have collaborated in the research for this thesis. Common denominators for the examples are: the load-structure-interaction, a strive to create beauty or curiosity, and the architectural scale. Where special areas of interest were: movement driven by passive forces such as wind, loose/flexible textiles, textile as a load-carrying structure, and lightweight structures. Depending on which field a person is active within these would be interpreted differently, which broadened the view of the research for this thesis. The phenomena and examples were then further studied through searches in Chalmers' university library (with both physical books and databases) and on Google.

The other part was an attempt to (more objectively) map the field of study that could be defined through the first part of the literature. For this a structured literature search in a selection of databases was made. The number results found in this is summarised in

Table 3.2 where the relevance of the paper or book was evaluated through a flowchart (Figure 3-1) that was developed to quickly sort the findings and to rely less on intuition. In the flowchart, "textile-like" refers to either the behaviour, or the logic of the material, based on the definition made in section 2.1.2, this includes, for example, plastic membranes, such as ETFE foil, and stiffer woven structures. A material was considered to be flexible if it had a significant lack of bending stiffness.

A scan of the titles, of the results, from the databases ProQuest, Web of Science, and Scopus, reviled few results with higher scoring. It was therefore decided to also search at Google Scholar. With the same search words (textile architecture wind) the outcome was approximately 44 500 results, showing a need to narrow the search. Words that have to do with movement was also added to the search, and, as a lot of the previous results had been about topics that lie outside the scope of this research, a few exclusion words were added in an attempt to filter these types of results out (see Table 3.2 for more details about the searches). Common topics that came up in the searches but were deemed to be outside the scope was: textile formwork or reinforcement of concrete or plastics, papers about archaeology and past civilisations, wind turbines, clothing, and fashion. Using exclusion word for these topics reduced the results to only 17, at first, which suggested that the search was to narrow. To approximately 4510, when the requirement of the exact phrase of "textile architecture" was removed. Since the results were listed according to relevance it was decided that it would be sufficient to, at this stage, only look at the first 300 results to get a satisfactory picture of the field. The database CumInCAD was also searched but generated no results which included all search words.

Further filtration of the results was made by reading abstracts and/or key parts of the texts. Which generated a total of 24 papers, scoring 3 or higher, in the flowchart, and only 2 publications were given a score of 5.

Table 3.2 Databases and search words used to scan the field, and the results of the searches. (search made 2019-08-08). Results with a score of 2 or higher was kept for a second round of evaluation and only texts scoring 3 or higher were kept in the second filtering process.

Database	**Search words**	**Number of results**	**Filtered results**	**Further filtration**
ProQuest	textile N/1 architecture wind	431	33	9
Web of science	textile architecture wind	23	0	0
Scopus	textile architecture wind	28	9	3
Google Scholar	wind textile architecture movement moving OR kinetic OR dynamic -archaeology -concrete -rotor -composite -ceramic -"Fibre Reinforced" -anthropology -empire -"folk art" -wearable -"arts and crafts" -erosion -"urban fabric" (not including patents)	4510 (only gone through the first 300 results, sorted by relevance)	16*	12
Google Scholar	"textile architecture" wind textile architecture movement kinetic OR dynamic -archaeology -concrete -rotor -composite -ceramic -"Fibre Reinforced" -anthropology -empire -"folk art" -wearable -"arts and crafts" -erosion -"urban fabric (not including patents)	17		
CumInCAD	{keywords} =~ m/textile/i and {keywords} =~ m/wind/i	0	0	0
CumInCAD	{content} =~ m/textile/i and {keywords} =~ m/wind/i	0	0	0
			=58	=24

* Number of new, relevant sources. Excluding titles that have already been collected through other databases

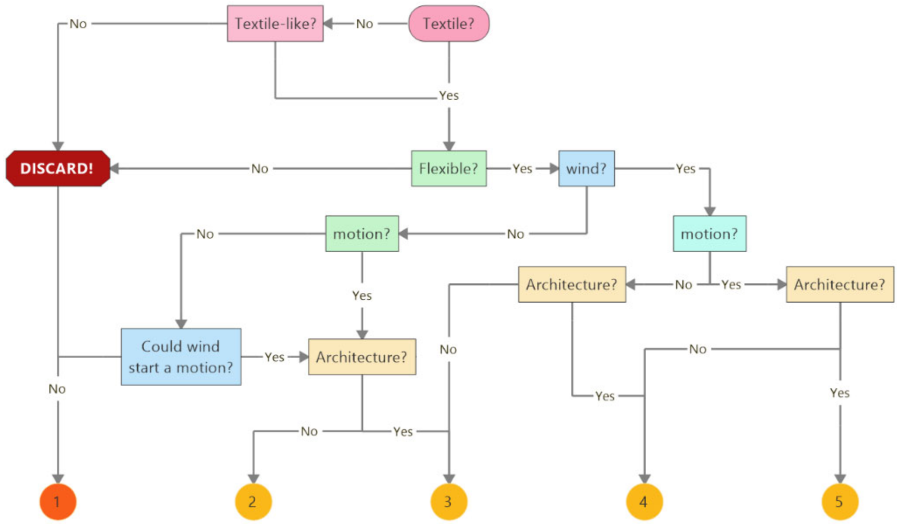


Figure 3-1 Flowchart to establish relevance of paper or book, with textile focus.

To get a better grasp of what has been written about computer simulations and computer aided design revolving around either wind or textiles, within the field of architecture, the database CumInCAD was searched with the keyword wind and the keyword textile (Table 3.3). As CumInCAD is a database for publications about computer aided architectural design, it was concluded that the results from these searches painted a satisfactory picture of these fields (and how little it is that has been written).

Table 3.3 Search results, using keywords in CuminCad. (search made 2019-08-08)

Database	**Search words**	**Number of results**	**Filtered results**	**Further filtration**
CuminCad	{keywords} =~ m/wind/i	40	8*	
CuminCad	{keywords} =~ m/textile/i	32	7*	

3.1.2 Design inquiries

The general goal for the explorations within this research has been to explore a phenomenon or a research question, without knowing exactly what to find and striving to keep an open mind to unexpected outcomes. They were recorded through photographs, videos and notes, and the outcome reflected upon according to the research question.

In *Vägen till verket* (1998) Ulf Jansson talks about the role of sketching for an architect as explorations of the situation and specific factors for the project in question. He relates this to Donald Schön's expression *reflexion in action* (Schön, 2011) (compared to reflexion after action). In this research the prototypes and explorations could be said to be the some of the sketches. Often the expected outcome (if expectations existed) would not be the same as the actual outcome, much due to reflexions during the process leading to new input and unexpected turns in the explorations. Like a dialogue with the making/piece (i.e. research by design, as described in the beginning of this chapter).

The design inquiries in this thesis could be divided into three categories: understanding the effect of textile structure on the behaviour in wind, how to document textile movement in still media, and how to work with textiles in digital simulations. All them with the overarching goal of understanding how textiles behave and/or move.

3.1.2.1 Understanding the behaviour of textiles moving in the wind?

The geometric, expressive and formational phenomena in the textile subjected to the influence of wind or airflow require the development of hands-on strategies. That enables the researcher to participate in the process of textile transformation from the perspective of a designer or an artist, working very close with the material. There is a considerable amount of knowledge about the material that can be only be gained by directly engaging in design with it. Arguably everyone has knowledge about the behaviour of textiles, formed by wearing clothes and the textiles that surround everyday life. However, in general, few reflect on the creases and waves, that appear in the fabric, or try to predict them.

Knitted textiles with varying densities and structures has been observed as airflow was applied. The samples were mounted on frames with sizes adjusted to their respective sizes. All samples were then exposed to airflow using a dedicated fan. The airflow was generated using a Trotec R TTW 45000 Wind Machine. More detailed descriptions of methods and set-up of these studies can be found in the appended papers summarised in 4.1 and 4.2.

3.1.2.2 Visualise motion

Research on textiles exposed to wind touches upon phenomena that are, in principle, dynamically changing with time. Therefore, it is challenging to communicate it via static media, such as a text or single photograph. Something that is of importance not only in order to communicate not only academic research, but also for designers (e.g. architects and engineers) working with moving structures, who need to be able to communicate the designs to clients.

Photography as a visualisation tool has been used and challenged with the question: Can motion be seen on a still image? Is it possible to communicate textiles put in motion by airflow in a media that is still, mute and without the tactile sensation of the airflow? This design inquiry has been on-going throughout the thesis and photo investigations can be found in section 2.5 as well as in the appended papers summarised in 4.1 and 4.2. The goal has been to strive towards capturing the movement of the air and textiles in single images, rather than creating a time-laps, as display space is generally limited.

3.1.2.3 Computer models and digital simulations

For the studies of textile behaviour, especially in combination with wind, it is difficult to find a readily available computer software which allow the large deformations and interaction abilities, sought within this thesis. Therefore, own written scripts and programming was deemed to be a better option, as it gave a better control over the calculations as well as giving a bigger freedom.

An initial study was the conceptual design of tensioned textile structures. For this an existing computer software was further developed to include the possibility to design and analyse tensile membrane structures. This was done through programming in C# and Microsoft Visual Studio 2010. The sought equilibrium shapes were reached through using the method of dynamic relaxation (DR), following the steps described by Barnes (1999), where the textile material was simplified into a two-dimensional surface. A more detailed description of this can be found in section 2.4.3 and in the appended paper summarised in 4.3. As well as these more static textiles structures, simulations of textiles moving in wind was studied through design investigations. In the investigations it was important to be able to control some aspects of the wind as well as the structure of the textile and its boundary conditions (i.e. the digital mounting). For the purpose of design investigations, it was preferable to have simulations in real time, so that both the initial design as well as the effect of different interventions could be seen and reacted upon. Simulations of such large deformations, as the ones exhibited by a flexible material, like textiles, effected by forces from wind, is difficult to handle for traditional fluid simulations software (see section 2.5.3). Thus, an SPH (smoothed particle hydrodynamics) inspired approach, was chosen order to create high speed simulations of this behaviour. This type of simulations, where both the wind and the textile is represented by a set of particles (see section 2.5.3, for more info about SPH), is favoured for animations of films and computer games. Here two different methods were tested, the first being the, open source, software Flexhopper (Felbrich, 2017/2020), a plug-in for Rhinoceros® and Grasshopper®, and the second being a script, developed by Chris Williams and the author, written in Processing. More about this in the appended paper summarised in 4.2.

4 Summary of papers

The papers summarised in this chapter cover different aspects of the research field. Common for them all is that focus is on the conceptual or early design phase of textile architecture.

4.1 Paper A

Exploring expressive and functional capacities of knitted textiles within the context of wind

The appended paper (Hörteborn & Zboinska, 2020) is the Authors' original manuscript/preprint version of the paper which is submitted. It applies a research by design methodology and forms an initial study for the application of knitted textiles improving environmental factors in urban areas.

Abstract:

This paper explores the design possibilities with knitted architectural textiles subjected to the action of wind. The purpose is to investigate how such textiles could be applied to alter the usual static expression of exterior architectural and urban elements, such as facades and windbreaks. The design investigations were made on manual knitting machines, with two iterations produced on a CNC flat knitting machine. Four knitting techniques - tuck stitch, hanging stitches, false lace, and drop stitch - were chosen and explored based on their ability to create a three-dimensional effect on the surface level as well as on an architectural scale. The conducted experiments, in which the textile samples produced, using those four techniques, are subjected to a controlled action of airflow, indicate that especially the drop stitch technique exhibits interesting potentials. Namely, the variations in the drop stitch pattern generate not only an aesthetic effect of a volumetric expression of the textile architectural surface but also seem beneficial in terms of wind reduction. Thus, these types of knitted textiles could be applied to design efficient architectural elements that are efficient in terms of improving the aesthetic user experience and comfort in windy urban areas.

Keywords: Textile architecture, knitted textiles, kinetic architecture, wind, aesthetic qualities, geometric expression

4.2 Paper B

Architecture from textile in motion

This paper (Hörteborn et al., 2019) is written for the IASS 2019 conference and is based on the findings from the workshop "Textile architecture (in)formed by wind: Design processes and tools" held at the conference Advances in Architectural geometry (AAG) 2018 (Hörteborn et al., 2018). It was written in collaboration with Malgorzata A. Zboinska, Delia Dumitrescu, Chris Williams, and Benjamin Felbrich.

Abstract

Wind is one important concern when it comes to its impact on textile structures within architecture. One method to limit wind-caused displacements is to heavily pre-stress the structures. We discuss an alternative approach, in which wind is seen as a positive design parameter for architectural textiles. We explore how one could work with the shape and internal structure of the textile to design architectural structures which become kinetic volumes when airflow is applied. The implications of such a design approach are formulated based on a two-day workshop at the conference Advances in Architectural Geometry (AAG) 2018. The explorations embraced digital and physical simulations of textile behaviors arising from the presence of wind. Smart textiles, whose structures can be changed using heat, were employed to explore how the geometrical expressions of textiles under wind load can be affected through local internal textile property changes. The ambition was to investigate the possibility of dynamically altering the 3-dimensionality of the textiles by reshaping them in real-time using airflow. The main conclusion from the workshop is that the dialogue between the digital and physical simulations seems to play an important role in supporting and enhancing the process of designing the geometrical expressions of textiles subjected to dynamic influence. A combination of the digital and the physical design tools enables the creation of a unique workflow to generate architectural design typologies that would have been difficult to develop if such complementary design tools have not been employed.

Keywords: Textile architecture, architectural form design, digital wind and textile simulation, physical wind simulation, research workshop

4.3 Paper C

Conceptual design and analysis of membrane structures

This paper (Henrysson et al., 2016) (written before name-change to Hörteborn) focuses on the form finding and design methods of tensile textile structures, indicating a gap between the form finding and structural analysis of the structures and the architectural design. It aimed to investigate if form finding and analysis of membrane structures could be more closely linked. A program/tool was developed, for initial design and analysis of the structures, on a conceptual stage, within the same CAD-environment as is used for the architectural design. Co-authors for the paper were: Jens Olsson, Al Fisher and Mats Ander.

Summary. In this work one approach for formfinding and analysing tension membrane structures is described. Focus has been on the conceptual stage. For this the computer software SMART Form has been further developed, enabling the possibility to do real-time formfinding and analysis of fabric structures. The software is based on a method where the orthotropic membrane is modeled with a triangular mesh, where the mass is lumped on the nodes. As a computational tool dynamic relaxation is used to find the static equilibrium configuration for the structure. The advantage with this is that there is no need for formulation and manipulation of matrices common in the finite element method.

Keywords: Tensile structures, Fabric Structures, Formfinding, Dynamic Relaxation

5 Conclusions and discussion

This thesis explored the concept of *textile architecture informed by wind* through the intersection between the fields: textile architecture, lightweight structures, and wind informed architecture. The overlaps of two out of three fields were defined as: tensile structures, wind in combination with textiles, and kinetic architecture. This description and structuring of the research field is part of the answer to the first research question for this thesis:

> How can the field *textile architecture informed by wind* be systematically described to clarify central aspects of textiles and wind in architecture, and through them act as inspiration for new applications?

In the conducted literature study, important findings that can serve as inspiration for new applications are:

- Porous materials like textiles can be highly suitable for designs aiming to achieve comfortable wind environments.
- When limiting textile architecture to only tensile structures, the designs are also limited to anticlastic geometries.
- Design of a kinetic structure could be made through restricting parts of the possible mechanical actions.
- Inspiration can be drawn from performances like dancers in voluminous light clothing. Which is, in essence, a structure that holds and directs the textiles' movement through the air.

The results of the research indicated that the field of textile architecture informed by wind is a relatively uncharted territory. However, knowledge as well as inspiration can be found in examples outside the field of architecture, such as performing arts, art installations, sailing, and fashion.

Furthermore, from the literature study, presented in chapter 2, conclusions can be drawn regarding digital simulation of loose textiles on an architectural scale. Firstly, these structures require different geometries for the material models depending on the type of textile. Secondly, for the simulation of these structures interacting with the wind, a mesh-free simulation is preferable, at a conceptual stage. This because the more traditional mesh-based wind simulation methods are unpractical for such large deformations. Which begins to answer the second research question:

> How can an architectural design process, for stiff and/or flexible textiles, be supported by digital (numerical) tools, appropriate representations, and explorative use of prototypes?

The papers summarised in chapter 0 explore how different forms of prototypes can aid the architectural design process. Paper A (Hörteborn & Zboinska, 2020) focused on physical prototypes and showed examples of how they could be used to draw conclusions regarding design opportunities. The samples were observed and, subjectively, analysed in terms of desired aesthetic expressions. Specifically, four different knitting techniques were explored and how these techniques affected the textiles' behaviour when subjected to airflow. Especially the drop-stitch technique exhibited interesting potentials. The pattern had a variating stitch-pattern that generated aesthetic effects of a voluminous expression of the architectural surface and, at the same time, seemed beneficial in terms of wind reduction. It was also noted that several thresholds might hinder the design of knitted structures in an architectural context. In general, there is a language barrier between the textile designers and the architects. It is also difficult to translate drawings and sketches from the architects' software to the design software for the knitting machines and vice versa. Although some authors (McCann et al., 2016; Narayanan et al., 2018; Popescu et al., 2018) presented methods of transforming three-dimensional meshes representing architectural surfaces to knitting patterns, which might be useful in a cross-disciplinary collaboration.

In paper B (Hörteborn et al., 2019) a mix of physical prototypes and computer simulations were explored. It was concluded that the dialogue between the digital and physical simulations seems to play an important role in supporting and enhancing the process of designing the geometrical expressions of textiles subjected to airflow. Paper C (Henrysson et al., 2016 (NKA Hörteborn)) focus on the digital simulation of tensioned textile architecture, on a conceptual stage. For structures of this kind computer models are almost essential, and the possibility to interact in real time with the model, as in the presented tool, can be a great advantage in an early design stage.

These examples of both digital and physical prototypes show opportunities for supporting a design process of both tensioned as well as loose textile structures, on an architectural scale. This design process is made complicated by the architects' limited knowledge about textiles, as well as the difficulties with representing textiles in physical scale models. Aspects that further support the claim that a mix of physical as well as digital models are beneficial in a design process, especially on a conceptual stage.

Why chose to work with physical models, when so much could be done in the computer?

Arguably computer simulations and computer models are good at a lot of things and can save money and material recourses. However sometimes a physical model can give answers which would be very difficult to acquire through digital simulations. In cases when test data are readily available and numerical answers are sought computer models are, usually, the best option. Although there are exceptions to this, e.g. for wind simulations, physical wind tunnel tests are still important (Kraft, 2010). In other cases, and, especially, with more artistic explorations a better understanding of material, scales, and physical phenomena can be gained through models that can be touched, and physically walked around and interact with in different ways. It could also be argued that it is easier to explore a material or phenomena, with physical experiments, especially open-ended explorations. A computer model requires well defined values and inputs, which might be difficult to give in initial explorations (this applies for both scientific as well as artistic experiments). In this research textiles have been explored both in computer models and in physical set-ups. The simulations of textiles in wind would have been very difficult to evaluate without having explored the textile material in physical models in parallel. Still, initial iterations of different physical models could be quicker to test in the computer first, even if computer models do not give the full picture. On an architectural scale it is unpractical to build physical models of entire buildings in the scale of 1:1. Consequently, neither physical nor computer models, alone, will give the full picture of the finished design.

5.1 Discussion about sustainability aspects

We need to make changes in the way we build, in order to have a chance of reaching the zero-carbon dioxide emission target. 2014 the manufacturing industry stood for 21% of the carbon dioxide emissions, of which a large part came from the building industry. By 2060 it is predicted that the world's building stock will have doubled, the equivalent of building one New York City per month over the next 40 years (Gates, 2019). Consequently, this must be built sustainably.

The building design governs the amount and type of building materials used and thus the amount of emissions and exploitation of resources. Today concrete and steel are the dominating building materials in the world, both of which emit a high amount of carbon dioxide during production/manufacturing (Intergovernmental Panel on Climate Change & Edenhofer, 2014, p. 758). Building lighter structures is a way of economizing with resources and emissions. Using textiles as building materials is one way to build light. Jörg and Mike Schlaich (n.d.) claim that lightweight structures are sustainable, not only, from an ecological point of view, by reduction of material waste, but also from a social and cultural point of view (more about this in section 2.3). These types of structures ads value and time to craftsmanship, which could result in more expensive buildings, which in turn could make them more valued and better cared for, which, from an ecological point of view, would be positive. A potential consequence of, economically, more expensive buildings is that it might push poorer people out of the market. However, the price of a building also depends on the cost of building materials. If the price of materials would depend more on the harm they cause the environment, it might result in a market where materials once again cost more than labour and craftsmanship.

Hedenus, Persson, and Sprei (2018) write about the concept of low and high substitutability, where high substitutability aligns with the concept of low sustainability and low substantiality is similar to high sustainability. I advocate low substitutability and believe that the exploitation of the Earth's rescores needs to be stopped. To make this possible, I argue that, we need to change our lifestyle (concept: sufficiency) or, in this case, the way we look upon architecture and buildings. This applies to both how much space we need and how much material and enclosure we need to create that space. One way of enabling lifestyle changes is to build more flexible buildings. Meaning that the building could be used in different ways or have different functions, or it could be that the building could be disassembled when not needed anymore and instead moved to where it is needed. This could apply to the entire building or parts of it. To enable this, light and easily transported building materials are required, like most textiles. One example of where this type of thinking was integrated into a design is the London Olympic stadium. Where the top part of the arena, built with steel and textiles, was designed to be dissembled after the games, to better suit audiences sizes after the Olympic games (Nimmo et al., 2011). Different tents and pneumatic structures used as shelters for refugees and after natural disasters are also examples of structures that are transported to where they are needed. These concepts could be applied in a wider context, for instance, office or residential applications.

In addition to lifestyle changes, there is a need to find new technical solutions to the production of building material and efficient production methods for the built structure, perhaps also redefine what qualifies as a building material. Through, for example, choosing better and more sustainable material i.e. recycled materials or materials from a renewable resource. In this context, textiles can be a good option, as textile fibres can be produced from a range of different materials, including bio-based and recycled products. It might seem strange to advocate for more use of textiles when news about the backside of the clothing and fashion industry today is making headlines. Reports about textile waste, high water demand, poor working conditions (at all levels of the industry), pollution, and high amounts of chemicals used in production have surfaced in the last years (Cristiansson, 2019; Drew & Reichart, 2019; 'UN Launches Drive to Highlight Environmental Cost of Staying Fashionable', 2019). Reports that not only visualises the strain textiles put on the ecological environment but also demonstrate a great injustice as the luxury consumption of people in rich countries harms both the people and the living environment in (mainly) developing countries. There are, however, signs suggesting that we are now at the beginning of a transformation for the textile industry. Numerous examples show possibilities to create environmentally friendly textiles, both from natural renewable recourses (like cotton and wool) but also recycled textiles and waste materials.

5.2 Future research

The research presented in this thesis opens up for future studies. In particular, further research is needed to study the effects that loose textile structures could have on the wind comfort. It should also be explored how to design the textile structures to reach the desired aesthetic appearance in the presence of wind, while remaining interesting also in calm weather.

Further work could be done with design prototypes, working with designs at a larger scale as well as site-specific installations. This allows for studying textiles in the scale of 1:1 as well as adding complexity in terms of wind coming from multiple directions. One application that could be explored is how textile structures could be designed and used to improve the aesthetic user experience and comfort in windy urban areas? As mentioned in section 2.2 to reduce wind it can be beneficial to use porous structures, such as textiles, to 'block' the wind. Using loose textiles in a design can allow the wind to shape the textiles in a predefined manner and create an aesthetic as well as an intriguing kinetic structure that at the same time creates a comfortable wind climate. Theoretically, the energy from the wind that is transferred into motion in the textile structure should reduce the wind. It could be interesting to investigate whether this transferred energy is enough to make a difference in the perceived comfort.

A suggestion for a second study is to apply designs of loose textile structures to a façade, to create an expressive textile surface with proneness to kinetically and observably changing change its shape. When mounting structures to a building the wind is restricted from pushing on the design from behind. This puts different demands on the pattern, compared to a design of a freestanding structure like a windbreak. The main goal of this study would be to improve the aesthetic user experience. However, also in this case, it would be interesting to investigate whether the textile structure could absorb a noticeable amount of the wind energy and thus generate a more comfortable wind climate close to the façade.

In both cases, explorations should preferably be done through a combination of computer simulations and physical prototypes. This would both be beneficial for the design as it has the potential to ease the design process and reduce material costs but would also give more clarity in the question of limitations and accuracy of computer simulations, for these types of structures.

Glossary

CFD	Computational Fluid Dynamics
DR	Dynamic relaxation. A computational method developed by Alistair Day (1965)
FEM	Finite Element Method
FSI	Fluid Structure Interaction
SPH	Smoothed Particle Hydrodynamics. A mesh-free simulation method for solid mechanics and fluid flow
Tensile structures	Pretensioned cable-net or membrane structures
Textile	Here defined as a material that: Have a thickness that is much smaller than length and breadth (z << x or y). Consists of fibres or structural members that in some way interlock and would unravel if one “tread” were to break. Have very low bending stiffness.
Wind	Naturally occurring airflow

References

Al-Masrani, S. M., & Al-Obaidi, K. M. (2019). Dynamic shading systems: A review of design parameters, platforms and evaluation strategies. *Automation in Construction*, *102*, 195–216. https://doi.org/10.1016/j.autcon.2019.01.014

Araújo, M., Fangueiro, R., & Hong, H. (2004). Modelling and simulation of the mechanical behaviour of weft-knitted fabrics for technical applications: Part III: 2D hexagonal FEA model with non-linear truss elements. *AUTEX Research Journal*, *Vol. 4*(1). http://repositorium.sdum.uminho.pt/

Armijos, S. J. (2008). *Fabric architecture: Creative resources for shade, signage, and shelter* (1st ed). W.W. Norton.

Arnold, M., & Schiehlen, W. (2009). *Simulation techniques for applied dynamics* (Vol. 507). Springer Science & Business Media.

Aynsley, R. M. (1999). Shape and Flow: The Essence of Architectural Aerodynamics. *Architectural Science Review*, *42*(2), 69–74. https://doi.org/10.1080/00038628.1999.9696854

Badarnah, L. (2017). Form Follows Environment: Biomimetic Approaches to Building Envelope Design for Environmental Adaptation. *Buildings*, *7*(2), 40. https://doi.org/10.3390/buildings7020040

Bahadori, M. N. (1978). Passive Cooling Systems in Iranian Architecture. *Scientific American*, *238*(2), 144–155. JSTOR.

Baker, W. F., Beghini, L. L., Mazurek, A., Carrion, J., & Beghini, A. (2015). Structural innovation: Combining classic theories with new technologies. *Engineering Journal*, *52*, 203–217.

Barnes, M. R. (1999). Form Finding and Analysis of Tension Structures by Dynamic Relaxation. *International Journal of Space Structures*, *14*(2), 89–104. https://doi.org/10.1260/0266351991494722

Barozzi, M., Lienhard, J., Zanelli, A., & Monticelli, C. (2016). The sustainability of adaptive envelopes: Developments of kinetic architecture. *Procedia Engineering*, *155*, 275–284.

Beukers, A., & Hinte, E. van. (2005). *Lightness: The inevitable renaissance of minimum energy structures* (4., rev. ed.). 010 publishers.

Blevins, R. D. (1990). *Flow-induced vibration.* (Depending on RTAC solution; 2. ed.). Van Nostrand Reinhold; Chalmers Library Print Collection. https://search.ebscohost.com/login.aspx?direct=true&AuthType=sso&db=cat07470a&AN=clc.6144e507.7a43.46af.ad6a.a222a07862c7&site=eds-live&scope=site&custid=s3911979&authtype=sso&group=main&profile=eds

Brocklehurst, S. (2013, June 3). Faulty tower: The £10m white elephant. *BBC News*. https://www.bbc.com/news/uk-scotland-22509056

Buckminster, F. R. (1962). *Tensile-integrity structures* (United States Patent No. US3063521A). https://patents.google.com/patent/US3063521A/en

Chilton, J., & Isler, H. (2000). *Heinz Isler*. Telford.

Cirio, G., Lopez-Moreno, J., & Otaduy, M. A. (2017). Yarn-Level Cloth Simulation with Sliding Persistent Contacts. *IEEE Transactions on Visualization and Computer Graphics*, *23*(2), 1152–1162. https://doi.org/10.1109/TVCG.2016.2592908

Creswell, J. W. (2014). *Research design: Qualitative, quantitative, and mixed methods approaches* (4th ed). SAGE Publications.

Cristiansson, T. (2019, November 27). Turkiets döda floder – textilindustrins mörka baksida—Nyheterna—Tv4.se. In *Nyheterna*. https://www.tv4.se/nyheterna/klipp/turkiets-d%C3%B6da-floder-textilindustrins-m%C3%B6rka-baksida-12512825

Davidson, L. (2018). *An Introduction to Turbulence Models*. Chalmers University of Technology. http://www.tfd.chalmers.se/~lada/postscript_files/kompendium_turb.pdf

Day, A. S. (1965). An introduction to dynamic relaxation(Dynamic relaxation method for structural analysis, using computer to calculate internal forces following development from initially unloaded state). *The Engineer*, *219*, 218–221.

Drew, D., & Reichart, E. (2019, January 10). By the Numbers: The Economic, Social and Environmental Impacts of "Fast Fashion". *World Resources Institute*. https://www.wri.org/blog/2019/01/numbers-economic-social-and-environmental-impacts-fast-fashion

Eberhard, P., & Schiehlen, W. (2006). *Computational dynamics of multibody systems: History, formalisms, and applications*.

Elnokaly, A. M. (2014). CFD Analysis of tensile conical membrane structures as microclimate modifiers in hot arid regions. *Civil Engineering and Architecture*, *2*(2), 92–102. https://doi.org/DOI: 10.13189/cea.2014.020204

Engel, H. (2013). *Tragsysteme =: Structure systems* (5. Aufl). Hatje Cantz.

Felbrich, B. (2020). *Flexhopper* [C#]. https://github.com/HeinzBenjamin/FlexCLI (Original work published 2017)

Fiorito, F., Sauchelli, M., Arroyo, D., Pesenti, M., Imperadori, M., Masera, G., & Ranzi, G. (2016). Shape morphing solar shadings: A review. *Renewable and Sustainable Energy Reviews*, *55*, 863–884. https://doi.org/10.1016/j.rser.2015.10.086

Foqué, R. (2010). *BUILDING KNOWLEDGE IN ARCHITECTURE*. ASP. http://ebookcentral.proquest.com/lib/chalmers/detail.action?docID=4445858

Fortmeyer, R., & Linn, C. (2014). *Kinetic architecture: Design for active envelopes* (D. Fatih, Ed.). Images publishing.

Freiberger, M. (2007). *Perfect buildings: The maths of modern architecture*. Plus+ magazine.

Garcia, M. (2006). Prologue for a history and theory of architextiles. *Architectural Design*, *76*(6), 12–20.

Gates, B. and M. (2019). *Annual letter 2019 by Bill and Melinda Gates*. Gatesnotes.Com. https://www.gatesnotes.com/2019-Annual-Letter

Glück, M., Breuer, M., Durst, F., Halfmann, A., & Rank, E. (2001). Computation of fluid–structure interaction on lightweight structures. *Journal of Wind Engineering and Industrial Aerodynamics*, *89*(14–15), 1351–1368. https://doi.org/10.1016/s0167-6105(01)00150-7

Gordon, J. E. (1978). *Structures, or Why things don't fall down*. Penguin Books.

Hedenus, F., Persson, M., & Sprei, F. (2018). *Sustainable development: Nuances and perspectives* (P. Essunger, Trans.; First edition). Studentlitteratur.

Henrysson, E. (2012). *Conceptual design and analysis of membrane structures* [Master thesis, Chalmers University of Technology]. http://publications.lib.chalmers.se/records/fulltext/168816/168816.pdf

Henrysson, E., Olsson, J., Fisher, A., & Ander, M. (2016). Conceptual design and analysis of membrane structures. *29th Nordic Seminar on Computational Mechanics*, S8:2:c.

Heyman, J. (1999). *The stone skeleton: Structural engineering of masonry architecture*. Cambridge University Press.

Hörteborn, E., Dumitrescu, D., Williams, C., Zboinska, M., & Felbrich, B. (2018, April 11). *Workshop 9: Textile architecture (in)formed by wind: Design processes and tools* [Conference]. AAG 2018. http://www.architecturalgeometry.org/aag18/workshop-9-textile-architecture/

Hörteborn, E., & Zboinska, M. A. (2020). *Exploring expressive and functional capacities of knitted textiles exposed to wind influence* [Manuscript submitted for publication].

Hörteborn, E., Zboinska, M., Dumitrescu, D., Williams, C., & Benjamin Felbrich. (2019). Architecture from textiles in motion. *Form and Force*, 2316–2323.

Hosain, Md Lokman, & Fdhila, R. B. (2015). Literature Review of Accelerated CFD Simulation Methods towards Online Application. *Energy Procedia*, *75*, 3307–3314. https://doi.org/10.1016/j.egypro.2015.07.714

Hosain, M.L., Domínguez, J. M., Bel Fdhila, R., & Kyprianidis, K. (2019). Smoothed particle hydrodynamics modeling of industrial processes involving heat transfer. *Applied Energy*, *252*, 113441. https://doi.org/10.1016/j.apenergy.2019.113441

Intergovernmental Panel on Climate Change, & Edenhofer, O. (Eds.). (2014). *Climate change 2014: Mitigation of climate change: Working Group III contribution to the*

Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Janet Echelman: Breaking Down Boundaries with Art | Adobe Creative Cloud. (2017, February 15). https://www.youtube.com/watch?v=l3rIW9nJw3Y

Janson, U. (1998). *Vägen till verket: Studier i arkitekt Jan Gezelius arbetsprocess*. Chalmers Univ. of Technology.

John Morris Dixon. (2007). Suvarnabhumi Airport, Bangkok. *Architectural Record*, *08.07*.

Knippers, J., Scheible, F., Oppe, M., & Jungohann, H. (2012). *Kinetic media facade consisting of GFRP louvers*. https://www.knippershelbig.com/sites/default/files/pdf/cice2012_paper_kineticfacade.pdf

Koch, K.-M., Habermann, K. J., & Forster, B. (2004). *Membrane structures: Innovative building with film and fabric*. Prestel Publishing.

Korner, A., Mader, A., Saffarian, S., & Knippers, J. (2016). *Bio-inspired kinetic curved-line folding for architectural applications*. http://papers.cumincad.org/data/works/att/acadia16_270.pdf

Kraft, E. M. (2010). *After 40 years why hasn't the computer replaced the wind tunnel?* ARNOLD ENGINEERING DEVELOPMENT CENTER ARNOLD AFS TN. https://apps.dtic.mil/docs/citations/ADA530355

Kronenburg, Robert. (2014). *Architecture in motion: The history and development of portable building*. Routledge, Taylor & Francis Group.

Krüger, S. (2009). *Textile architecture = Textile Architektur*. Jovis.

Latour, B., & Yaneva, A. (2008). Give me a gun and I will make all buildings move: An ANT's view of architecture. *Explorations in Architecture: Teaching, Design, Research*, 80–89.

Lewis, W. J. (2003). *Tension structures: Form and behaviour*. Thomas Telford ; Distributors, ASCE Press.

Liddell, I., & Heppel, P. (2001). Turning with the Wind. *Civil Engineering (08857024)*, *71*(7), 38. Business Source Premier.

Liu, M. B., & Liu, G. R. (2010). Smoothed Particle Hydrodynamics (SPH): An Overview and Recent Developments. *Archives of Computational Methods in Engineering*, *17*(1), 25–76. https://doi.org/10.1007/s11831-010-9040-7

Llorens, J. I. de. (2015). *Fabric structures in architecture. [Electronic resource]*. Woodhead Publishing. http://proxy.lib.chalmers.se/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=cat06296a&AN=clc.b2195381&site=eds-live&scope=site

Marie louise fuller (United States Patent No. US518347A). (1894). https://patents.google.com/patent/US518347A/en

McCann, J., Albaugh, L., Narayanan, V., Grow, A., Matusik, W., Mankoff, J., & Hodgins, J. (2016). A compiler for 3D machine knitting. *ACM Transactions on Graphics*, *35*(4), 1–11. https://doi.org/10.1145/2897824.2925940

Menges, A., & Reichert, S. (2015). Performative Wood: Physically Programming the Responsive Architecture of the HygroScope and HygroSkin Projects. *Architectural Design*, *85*(5), 66–73. https://doi.org/10.1002/ad.1956

Michalski, A., Haug, E., Bradatsch, J., & Bletzinger, K.-U. (2009). Virtual Design Methodology for Lightweight Structures—Aerodynamic Response of Membrane Structures. *International Journal of Space Structures*, *24*(4), 211–221. https://doi.org/10.1260/026635109789968245

Michalski, Alexander, Kermel, P., Haug, E., Löhner, R., Wüchner, R., & Bletzinger, K.-U. (2011). Validation of the computational fluid–structure interaction simulation at real-scale tests of a flexible 29 m umbrella in natural wind flow. *Journal of Wind Engineering and Industrial Aerodynamics*, *99*(4), 400–413. https://doi.org/10.1016/j.jweia.2010.12.010

Moya, R., Salim, F., & Williams, M. (2014). Pneumosense Project. *Rethinking Comprehensive Design: Speculative Counterculture, Proceedings of the 19th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2014)*, 369–378.

Moya, R., Salim, F., Williams, M., & Sharaidin, K. (2013). *Flexing Wind*. http://papers.cumincad.org/cgi-bin/works/paper/ecaade2013_169

Narayanan, V., Albaugh, L., Hodgins, J., Coros, S., & Mccann, J. (2018). Automatic Machine Knitting of 3D Meshes. *ACM Transactions on Graphics*, *37*(3), 35:1–35:15. https://doi.org/10.1145/3186265

Nilsson, F., & Dunin-Woyseth, H. (2011). Building a culture of doctoral scholarship in architecture and design. A Belgian-Scandinavian case. *Nordic Journal of Architectural Research*, *23*(1).

Nilsson, F., & Dunin-Woyseth, H. (2012). On the Emergence of Research by Design and Practice-based Reseach Approaches in Architectural and Urban Design. In *Design Innovation for the Built Environment: Research by Design and the Renovation of Practice* (pp. 37–52).

Nimmo, A., Wright, S., & Coulson, D. (2011). Delivering London 2012: Temporary venues. *Proceedings of the Institution of Civil Engineers*, *164*(6), 59–64. ProQuest Central.

Olsson, K.-G. (2005). *Strukturmekanik & arkitektur: Om strukturmekanisk förståelse i gestaltningsprocessen*. Chalmers Univ. of Technology.

Otto, F., & Rasch, B. (2006). *Finding form: Towards an architecture of the minimal* (5th Edition). Axel Menges.

Otto, F., Vrachliotis, G., Kleinmanns, J., Kunz, M., & Frohn, M. (2017). *Frei Otto—Thinking by Modelling* (P. Kurz, Ed.; 1. Auflage). Spector Books.

Popescu, M., Rippmann, M., Van Mele, T., & Block, P. (2018). Automated Generation of Knit Patterns for Non-developable Surfaces. In K. De Rycke, C. Gengnagel, O. Baverel, J. Burry, C. Mueller, M. M. Nguyen, P. Rahm, & M. R. Thomsen (Eds.), *Humanizing Digital Reality: Design Modelling Symposium Paris 2017* (pp. 271–284). Springer. https://doi.org/10.1007/978-981-10-6611-5_24

Riedelsheimer, T. (2001). *Andy Goldsworthy: Rivers and Tides—Working with Time*.

Saadatian, O., Haw, L. C., Sopian, K., & Sulaiman, M. Y. (2012). Review of windcatcher technologies. *Renewable and Sustainable Energy Reviews*, *16*(3), 1477–1495. https://doi.org/10.1016/j.rser.2011.11.037

Santina Di Salvo. (2018). Kinetic Solutions for Responsive and Communicative Building Skin. *Advanced Materials Research*, *1149*, 86–97. https://doi.org/10.4028/www.scientific.net/AMR.1149.86

Schek, H.-J. (1974). The force density method for form finding and computation of general networks. *Computer Methods in Applied Mechanics and Engineering*, *3*(1), 115–134. https://doi.org/10.1016/0045-7825(74)90045-0

Schiehlen, W. (2007). Research trends in multibody system dynamics. *Multibody System Dynamics*, *18*(1), 3–13. https://doi.org/10.1007/s11044-007-9064-4

Schlaich, J., & Schlaich, M. (n.d.). *Lightweight structures*. https://architecture.mit.edu/sites/architecture.mit.edu/files/attachments/lecture/LightweightStructures.pdf?fbclid=IwAR2xwnKqr8DtWOO_QXmBcvI879GPRtOZtR5YdJVCVYNDdngMjiO9xsoHNpw

Schlaich, M. (2016). Homage–source of inspiration. *Structures and Architecture: Beyond Their Limits*, 330–337. https://books.google.se/books?hl=sv&lr=&id=DhANDgAAQBAJ&oi=fnd&pg=PA330&dq=Homage+%E2%80%93+Source+of+inspiration+schlaich&ots=UEGnZzz-Ko&sig=yJRSBtXoxQShuARxnvEi9nyHsCU&redir_esc=y#v=onepage&q=Homage%20%E2%80%93%20Source%20of%20inspiration%20schlaich&f=false

Schmeck, M., & Gengnagel, C. (2016). Calibrated Modeling of Knitted Fabric as a Means of Simulating Textile Hybrid Structures. *Procedia Engineering*, *155*, 297–305. https://doi.org/10.1016/j.proeng.2016.08.032

Schön, D. A. (2011). *The reflective practitioner: How professionals think in action* (Reprinted). Ashgate.

Schumacher, M., Schaeffer, O., Vogt, M.-M., & Scheuermann, A. (2010). *MOVE - Bewegliche Bauteile und Komponenten in der Architektur: Architecture in Motion - Dynamic Components and Elements*. Walter de Gruyter GmbH. http://ebookcentral.proquest.com/lib/chalmers/detail.action?docID=1020521

Sehlström, A. (2013). *Multiobjective topology optimization: Tracing of Pareto-optimal structures with respect to volume, compliance and fundamental eigenvalue*. https://odr.chalmers.se/handle/20.500.12380/184950

Sehlström, A. (2019). *Prestress in Nature and Technics* [Chalmers University of Technology]. https://research.chalmers.se/en/publication/511695

Semper, G. (2010). *The four elements of architecture and other writings* (H. F. Mallgrave & W. Herrmann, Trans.; First paperback edition). Cambridge University Press (Original work published 1989).

Shadloo, M. S., Oger, G., & Le Touzé, D. (2016). Smoothed particle hydrodynamics method for fluid flows, towards industrial applications: Motivations, current state, and challenges. *Computers & Fluids*, *136*, 11–34. https://doi.org/10.1016/j.compfluid.2016.05.029

Shelley, M. J., & Zhang, J. (2011). Flapping and bending bodies interacting with fluid flows. *Annual Review of Fluid Mechanics*, *43*, 449–465.

Snelson, K., & Heartney, E. (2013). *Kenneth Snelson, Art and Ideas* (First Ed.). http://kennethsnelson.net/

Spencer, D. J. (2001). *Knitting Technology: A Comprehensive Handbook and Practical Guide*. Taylor & Francis.

Tennekes, H., & Lumley, J. L. (1972). *A first course in turbulence*. MIT Press.

Tibert, G. (2002). *Deployable tensegrity structures for space applications* [KTH]. http://www.diva-portal.org/smash/get/diva2:9104/FULLTEXT01.pdf

Tomlow, J. (2016). Designing and constructing the Olympic roof (Munich 1972). *International Journal of Space Structures*, *31*(1), 62–73. https://doi.org/10.1177/0266351116642078

UN launches drive to highlight environmental cost of staying fashionable. (2019, March 25). *UN News*. https://news.un.org/en/story/2019/03/1035161

Van Dyke, M. (1982). *An album of fluid motion*. Parabolic Press Stanford.

Wang, D., & Groat, L. N. (2013). *Architectural research methods* (Second Edition). John Wiley & Sons, Incorporated.

Williams, C. (1990a). Generation of a class of structural forms for vaults and sails. *Structural Engineer*, *68*(12), 231–235.

Williams, C. (1990b). Travelling waves and standing waves on fabric structures. *Structural Engineer*, *68*(21/6).

Wu, Y.-C., Yang, A.-S., Tseng, L.-Y., & Liu, C.-L. (2011). Myth of ecological architecture designs: Comparison between design concept and computational analysis results of natural-ventilation for Tjibaou Cultural Center in New Caledonia. *Energy and Buildings*, *43*(10), 2788–2797. https://doi.org/10.1016/j.enbuild.2011.06.035

Figure references

Unless otherwise noted, all figures and diagrams are made by Erica Hörteborn

Figure 1-1
Dancer Arika Yamada, dancing with textiles in wind
Photo by Linda Wallander (08-03-2018). Re-printed with permission

Figure 2-2
Munich - Olympiapark 3, by Tiia Monto, licenced under CC BY-SA 3.0,
Uploaded: 14-08-2014
Retrieved: 10-09-2019, from:
https://en.wikipedia.org/wiki/File:Munich_-_Olympiapark_3.jpg

Figure 2-4 (left)
Illustration of weave made by Linda Wallander and Malin Borgny. Reprinted with permission, from:
Borgny, M., & Wallander, L. (2019). Textile Informed Structures—How to Braid a Roof Translating the logic of textile structure into the scale of architecture [MSc thesis]. Chalmers University of Technology.

Figure 2-7
a) Tjibaou cultural center,
Photo by Fanny Schertzer, licensed under the Creative Commons Attribution-ShareAlike 3.0 License
Retrieved: 15-06-2020, from:https://en.wikipedia.org/wiki/File:Tjibaou_cultural_center-Commons_transfer_2012-11-20.jpg#filelinks
b) Glasgow tower.
Copyright Adam Sommerville, licensed for reuse under Creative Commons Licence.
Retrieved: 12-06-2020, from: https://www.geograph.org.uk/photo/1480534

Figure 2-10
Flow around a cylinder at different Reynolds number
Illustration created by Erica Hörteborn, based on figure from:
Blevins, R. D. (1990). Flow-induced vibration. (Depending on RTAC solution; 2. ed.). Van Nostrand Reinhold; Chalmers Library Print Collection.
https://search.ebscohost.com/login.aspx?direct=true&AuthType=sso&db=cat07470a&AN=clc.6144e507.7a43.46af.ad6a.a222a07862c7&site=eds-live&scope=site&custid=s3911979&authtype=sso&group=main&profile=eds

Figure 2-12
Concrete shell roof ('Isler shell')
Copyright Chriusha (Хрюша) (1) / CC-BY-SA-3.0
Retrieved: 15-06-2020, from:
https://commons.wikimedia.org/wiki/File:Gartencenter_Wyss_Zuchwil_01_09.jpg

Figure 2-13
Needle Tower II, 1969
Image by Onderwijsgek, licenced under CC-BY-SA-2.5-NL
Retrieved: 15-06-2020, from:
https://commons.wikimedia.org/wiki/File:Kenneth_Snelson_Needle_Tower.JPG

Figure 2-15
Source of the diagram: Mike Schlaich
The graphic is done by xplicit Gesellschaft für Kommunikation mbH.
Reprinted with permission.

Figure 2-16
The Millennium Dome, London, UK
Photo by James Jin, CC BY-SA 2.0
Retrieved: 15-06-2020, from: https://www.flickr.com/photos/jamesjin/58712717

Figure 2-17
Suvarnabhumi, Bangkok
Image by TheDigitalWay from Pixabay
Retrieved: 08-06-2020, from: https://pixabay.com/photos/airport-gate-flight-1659008/

Figure 2-19
Image of a soapfilm model produced during a workshop, held at Chalmers University of technology 2018, by Emil Adiels, Tim Finlay, Isak Näslund, Puria Safari and Chris Williams
Photo by Emil Adiels. Re-printed with permission

Figure 2-24
(left) Loie Fuller dancing
Creator: Samuel Joshua Beckett
Source: https://www.metmuseum.org/art/collection/search/287816
This file was donated to Wikimedia Commons as part of a project by the Metropolitan Museum of Art.
Retrieved: 15-06-2020, from:
https://commons.wikimedia.org/wiki/File:Loie_Fuller_Dancing_MET_DP267670.jpg
(right) Patent drawing
Retrieved: 15-06-2020, from: https://patents.google.com/patent/US518347A/en

Figure 2-25
Dancer Arika Yamada, dancing with textiles in wind
Photo by Linda Wallander (08-03-2018). Re-printed with permission

Figure 2-27
Image from simulation created by Chris Williams, using a SPH approach.
Video retrieved: 17-09-2019, from: http://structure-geometry.eu/.
Re-printed with permission.

Figure 2-28
Photograph "Institut du Monde Arabe by Jean Nouvel - interior detail", by Steve Silverman taken on May 14, 2014.
Retrieved, 09-09-2019, from: https://www.flickr.com/photos/pov_steve/14794557711

Figure 2-29
Al Bahar Towers, photograph by Habitat CC BY-NC-ND 2.0
Retrieved, 21-08-2020, from:
https://www.flickr.com/photos/inhabitat/12331034465/in/photostream/

Figure 2-30
Mechanical movements in space through rotation and translation
Illustration created by Erica Hörteborn, based on figure in:
Schumacher, M., Schaeffer, O., Vogt, M.-M., & Scheuermann, A. (2010). MOVE - Bewegliche Bauteile und Komponenten in der Architektur: Architecture in Motion - Dynamic Components and Elements. Walter de Gruyter GmbH.
http://ebookcentral.proquest.com/lib/chalmers/detail.action?docID=1020521

Appendix A Equations for fluid dynamics

The mathematical description of wind is given by the Navier–Stokes equations:

Conservation of mass:

$$\frac{D\rho}{Dt} = \frac{\partial\rho}{\partial t} + \mathbf{v}\cdot\nabla\rho = -\rho\nabla\cdot\mathbf{v} = 0 \tag{5-1}$$

Conservation of momentum:

$$\overbrace{\rho}^{\text{“mass”}}\underbrace{\frac{D\mathbf{v}}{Dt}}_{\text{acceleration}} = \underbrace{\nabla\cdot\left\{\left(-p+\left(\zeta-\frac{2}{3}\,\mu\right)\nabla\cdot\mathbf{v}\right)\mathbf{I} + 2\mu\frac{1}{2}\left(\nabla\mathbf{v}+(\nabla\mathbf{v})^{\mathrm{T}}\right)\right\}}_{\text{Internal force}} + \underbrace{\rho g}_{\text{external force}} \tag{5-2}$$

Where p is the pressure, μ is the viscosity and ζ is the bulk viscosity. The density, ρ, is constant for an incompressible fluid (as in the case of wind around buildings).

As can be seen in This could be compared to the vorticity equation:

$$\boldsymbol{\omega} = \frac{1}{2}\left(\nabla\mathbf{v}-(\nabla\mathbf{v})^{\mathrm{T}}\right) = \frac{1}{2}\left(\frac{\partial v_y}{\partial x}-\frac{\partial v_x}{\partial y}\right) \tag{5-4}$$

Figure 5-1 aims to explain vorticity, through a 2d example (inspired by (Williams, 1990b)). You can see that by adding the two circled expressions (similar to equation (5-3)) the fluid gets “squeezed”, resulting in shear strain. By subtracting one term you create a rotation, resulting in vorticity (equation (5-4)).

the term $\nabla\cdot\mathbf{v}$ is a scalar describing the change in velocity in the three main direction, or that mass is conserved. $\nabla\mathbf{v}$ is the change in velocity all velocity components in the x, y and z-direction (i.e. 9 components). The term $\frac{1}{2}\left(\nabla\mathbf{v}+(\nabla\mathbf{v})^{\mathrm{T}}\right)$ in equation (5-2) is the rate of shear strain, $\boldsymbol{\gamma}$.

$$\boldsymbol{\gamma} = \frac{1}{2}\left(\nabla\mathbf{v}+(\nabla\mathbf{v})^{\mathrm{T}}\right) = \frac{1}{2}\left(\frac{\partial v_y}{\partial x}+\frac{\partial v_x}{\partial y}\right) \tag{5-3}$$

This could be compared to the vorticity equation:

$$\boldsymbol{\omega} = \frac{1}{2}\left(\nabla\mathbf{v}-(\nabla\mathbf{v})^{\mathrm{T}}\right) = \frac{1}{2}\left(\frac{\partial v_y}{\partial x}-\frac{\partial v_x}{\partial y}\right) \tag{5-4}$$

Figure 5-1 aims to explain vorticity, through a 2d example (inspired by (Williams, 1990b)). You can see that by adding the two circled expressions (similar to equation (5-3)) the fluid gets “squeezed”, resulting in shear strain. By subtracting one term you create a rotation, resulting in vorticity (equation (5-4)).

Table 5.1 The del operator

The del operator, ∇: $$\nabla = \left(\frac{\partial}{\partial x} i + \frac{\partial}{\partial y} j + \frac{\partial}{\partial z} k\right)$$ thus $$\nabla \cdot \mathbf{v} = \frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z}$$ and $$\nabla \mathbf{v} = \begin{bmatrix} \frac{\partial v_x}{\partial x} & \frac{\partial v_x}{\partial y} & \frac{\partial v_x}{\partial z} \\ \frac{\partial v_y}{\partial x} & \frac{\partial v_y}{\partial y} & \frac{\partial v_y}{\partial z} \\ \frac{\partial v_z}{\partial x} & \frac{\partial v_z}{\partial y} & \frac{\partial v_z}{\partial z} \end{bmatrix}$$

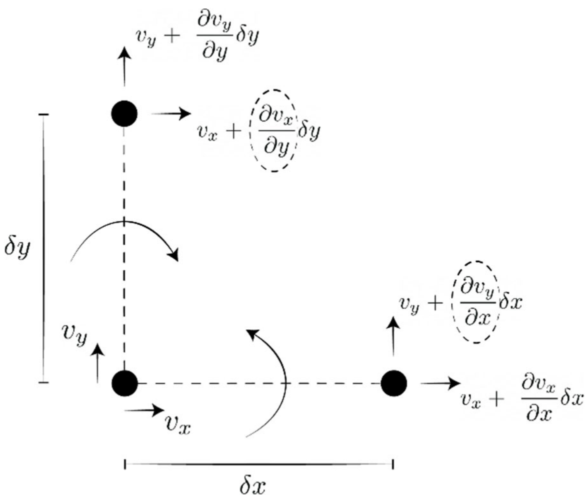


Figure 5-1 illustrating three fluid particles and their velocities at different positions. Note that the circled expressions are the ones that effects the rate of shear strain and vorticity, it is also the terms that rotates the fluid particles.