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Marta Gil Pérez

Integrative Structural Design of Non-Standard Building Systems:

Coreless Filament-Wound Structures as a Case Study

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Von der Fakultät Architektur und Stadtplanung der Universität Stuttgart
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"Structure is more than simply the means to realize a work of architecture, but a fundamental, inspirational quality" Mathew Nowicki

Acknowledgements

My journey from the end of 2017 until 2023 at the Institute of Building Structures and Structural Design of the University of Stuttgart (ITKE) comprises not only the research and development of this dissertation but also the challenge and excitement of three built projects with outstanding teams, the unforgettable experience of teaching in the ITECH program, a pandemic, and the birth of my three children, to whom I am most grateful.

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Zusammenfassung

Unsere Gesellschaft erlebt das Aufkommen neuartiger *nicht-standardisierter Gebäudesysteme*, welche durch digitale Technologien im Bauwesen ermöglicht werden. Der computergestützte Auslegungsprozess in Verbindung mit digitaler Fertigung und *Materialforschung* ermöglichen es über konventionelle Bauweisen hinauszugehen. Dies erfordert jedoch auch neue Arten der Planung und der Führung von Sicherheitsnachweisen. Ziel dieser Arbeit ist die Entwicklung einer integrativen Methodik für die strukturelle Auslegung sowie das Erarbeiten eines Arbeitsablaufs für Entwurf, Optimierung und Validierung nicht-standardisierter Gebäudesysteme. Hierzu wird ein mehrskaliger digital-physikalischer Ansatz vorgestellt, welcher Struktursimulationen mit kleinmaßstäblichen Modellen und Materialtests kombiniert und so die Optimierung sowie den Sicherheitsnachweis der Struktur ermöglicht.

In den ersten beiden Kapiteln werden Motivation, Ziele und Kontext der Forschung dargelegt. Anhand historischer Anmerkungen werden die Entwicklung der Tragwerksplanung wie auch die Schlüsselaspekte erläutert, welche in der Vergangenheit zu Innovationen und nicht- standardisierten Systeme geführt haben. Das kernlose Wickeln wird an dieser Stelle auch als repräsentatives Beispiel für nicht-standardisierte Gebäudesysteme vorgestellt.

Kapitel drei enthält die Veröffentlichungen, in denen die Entwicklung der integrativen Tragwerksplanungsmethoden anhand von kernlos gewickelten Strukturen als Fallstudie beschrieben wird. Alle Veröffentlichungen stützen sich auf kernlos gewickelte Proben oder in Originalgröße gebaute Demonstratoren, darunter der BUGA Faser Pavillon, Maison Fibre und der LivMatS Pavillon.

Die Kapitel vier und fünf fassen die Ergebnisse zusammen und verallgemeinern den Arbeitsablauf von kernlos gewickelten Strukturen auf nicht-standardisierte Gebäudesysteme in vier Untermethoden: mehrstufige Modellierung und Bewertung, strukturelle Charakterisierung, integrativer Auslegung sowie Optimierung und Sicherheitsüberprüfung. Die Diskussion verortet die integrative Strukturauslegung im historischen Kontext und analysiert die Strategien zum Nachweis der Sicherheit anderer nicht-standardisierter Systeme. In der Schlussfolgerung wird das Potenzial dieser Methodik hervorgehoben, die Diskrepanz zwischen Forschung und Industrie zu verringern und so das Vorantreiben innovativer Strukturen zu erleichtern.

Abstract

Our society is experiencing the emergence of novel *non-standard building systems* unlocked by digital technologies in the building sector. The utilisation of computational design processes and digital fabrication, coupled with the exploration of new *materiality*, bring the potential to break with conventional ways of building. However, they also demand new ways of designing and proving the structure's safety. This dissertation aims to develop an integrative structural design methodology and workflow to design, optimise and validate non-standard building systems. Therefore, a multi-scale, digital-physical approach is proposed, which combines structural simulation with small-scale models and material testing, allowing the structure's optimisation and proof of safety.

The first two chapters explain the research motivation, objectives and contextualisation. Historical remarks are given to understand the evolution of structural design and the key aspects that created innovation and non-standard systems in the past. Coreless filament winding (CFW) is also introduced here as a representative example of non-standard building systems.

Chapter three contains the publications that describe the development of the integrative structural design methodologies through coreless filament wound structures as a case study. All the publications are supported by CFW specimens or full-scale built demonstrators, including BUGA Fibre Pavilion, Maison Fibre and LivMatS Pavilion.

Chapters four and five summarise the results, generalising the workflow from CFW structures to non-standard building systems into four sub-methods: multi-level modelling and evaluation; structural characterisation; integrative design; and optimisation and safety verification. The discussion locates the integrative structural design in the historical context and analyses the strategies to prove the safety of other non-standard systems. The conclusion emphasises the potential of this methodology to *shorten the gap between research and industry*, facilitating the realisation of innovative structures.

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To Sara, Juan, and Teo

1. Introduction

The *digitalisation age* has brought progress to most engineering fields; however, the ways we built have not changed since the middle of the twentieth century, with the last advances in concrete and tensile structures. In research, the introduction of computational design tools, computer-aided fabrication methods and emerging material systems have already enabled the development of new *materiality* and potential fabrication techniques that can produce lighter, high-performative or more sustainable structures.
This building system can be considered **non-standard** when either the *design process* or the *proof of safety* of the structure need a different approach from the methods utilised at the time of being realised. Nowadays, these would mean structures that cannot be conventionally designed and verified by an analytical method such as finite element analysis (FEA), and are not covered by design guidelines, manuals and building codes. As a result, their design constitutes a challenge for engineers, but also an opportunity to rethink conventional structural design processes that can include integrative approaches and strategies to increase the confidence in the design.

Looking back into history, **characterisation**, **simulation**, **design**, and **evaluation** have been essential research areas integrating theories with experiments necessary to design new building systems capable of resisting and carrying loads. The advantages of digital tools combined with more experimental methods learnt from the past can help develop an **integrative structural design approach**, bridging the gap between research and practice and allowing the **proof of safety for novel and complex non-standard building systems**.

1.1 Motivation

With the increasing demand for new buildings and infrastructures, reducing waste, pollution and gas emissions in construction is becoming one of our society's challenges. In response to this problem and coupled with the developments in digital technologies, non-standard building systems are emerging in search of lighter, high-performative or more sustainable structures. These non-standard systems can result

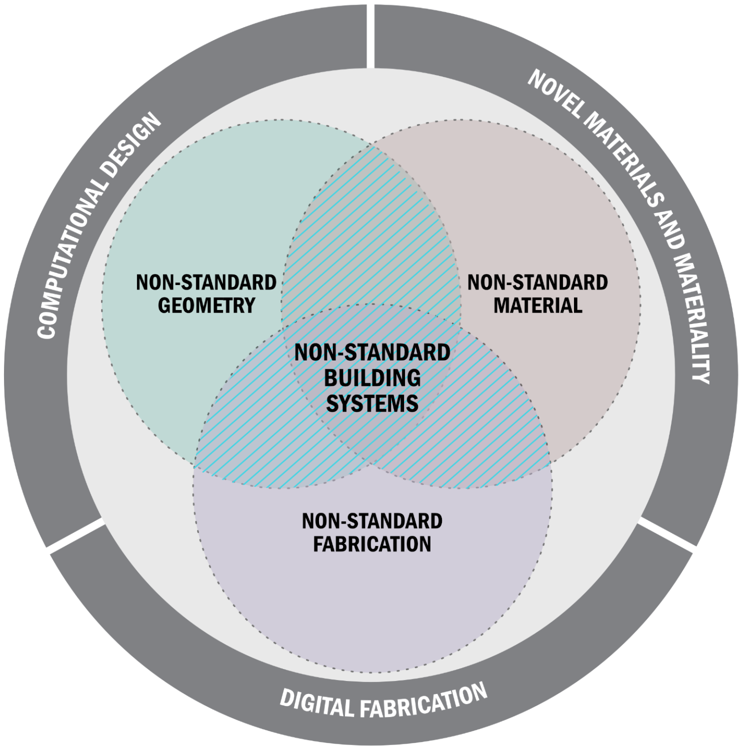


Figure 1.1
Non-standard Building Systems as the intersection of the application into construction of one or more of the following areas: computational design, digital fabrication and novel materials and materiality.

from developments in one or more of the following areas: computational design processes, digital fabrication methods, or emerging material systems (Figure 1.1).

Computational design processes, such as *parametric design*, have unlocked the realisation of non-standard geometries, which are frequently complex and require a *digital design workflow*. The structural design of these new geometries also needs to be integrated into the digital design workflow to obtain optimal results. An integrated structural design approach facilitates the reduction of material consumption by adapting the design to the most efficient structural performance.

The *advances in digital fabrication* have enabled automated construction, allowing the exploration of *materiality* in a *cyber-physical process*. The accuracy can be programmed, customising geometry and design digitally. These new methods, especially in their development stage, usually require *prototyping*. Besides, their architectural and structural design needs persistent interchange of fabrication parameters, as they can produce significant deviations in the final produced elements. Therefore, structural design should be agile and iterative, introducing physical and digital strategies.

Finally, *novel emerging materials* and *unconventional materiality* unfolded by digital fabrication are also being applied to the construction sector, achieving more sustainable or lightweight solutions. Structural design codes and simulation tools frequently do not support these new material systems, increasing the difficulties of proving their viability and safety. Their design is subjected to characterisation and understanding of the material behaviour and fabrication implications.

As can be seen, conventional structural design methods cannot respond to the design needs of non-standard building systems. Consequently, the transfer of the systems from research into practice is frequently challenging as structural integrity and safety cannot be proven. The current remedy to these problems is the application of high safety factors to their design, resulting in design modifications and higher material consumption. This strategy contradicts the building system's original aim, frequently related to the production of lightweight and sustainable structures. The engineering challenges vary from different projects but share some of the following aspects:

- The design and geometry are not defined until the last project stage.
- The simulation methods frequently cannot represent the complexity of the material or fabrication system.
- The material system or structural typology does not match conventional building codes.
- Prototyping and testing at full scale are frequently impossible for the complete system.
- Material characterisation needs to include the parameters related to the fabrication method to be used.

All of these aspects make evident that new approaches are needed to prove the feasibility and structural safety of the design. Motivated by bridging the gap between research and practice, enabling their construction in real applications, this research aims to provide integrative structural design methods to design, optimise and validate non-standard building systems.

1.2 Research objectives

The overarching research objective of this dissertation is the development of an integrated structural design methodology and workflow to validate the structural integrity and prove safety of non-standard building systems.

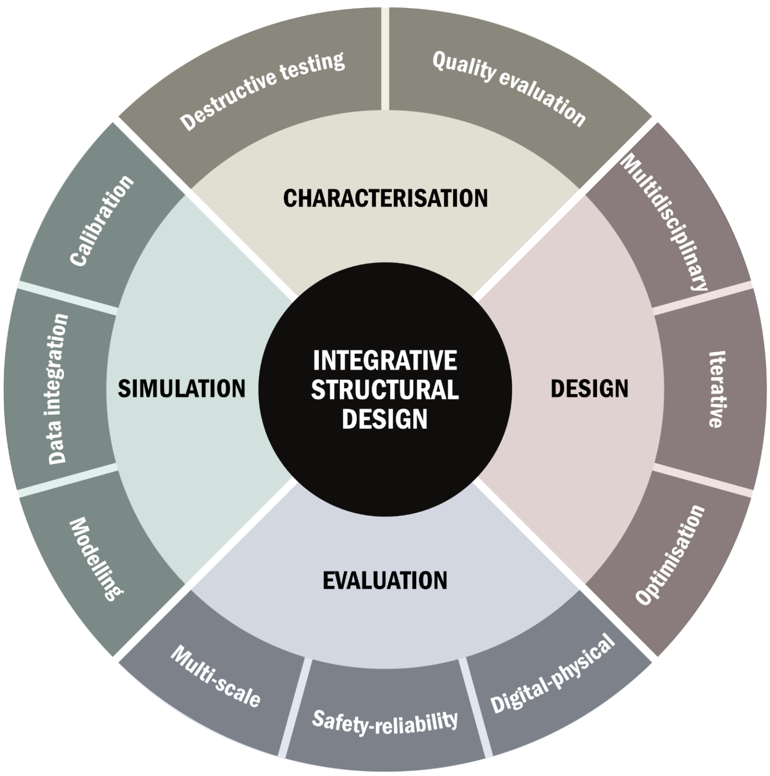
The work covers four research areas to achieve this aim: **characterisation**, **simulation**, **design**, and **evalu-**

ation, with specific objectives, as described below and illustrated in Figure 1.2.

- The material system needs to be *characterised* using either **destructive testing** or **quality evaluation** methods tailored to the design specifications and fabrication method.
- The *simulation* techniques employed need to be **calibrated** through different methodologies to improve the reliability of the results. The **modelling** approach and assumptions taken should be adjusted to the designed system, and strategies for **data integration** with other disciplines involved in the project (as computational design or fabrication data) have to be developed.
- The *design* of these non-standard systems should be **multidisciplinary** and include design **iterations** between the different fields, aiming for structural **optimisation** to achieve efficiency and fulfil the design goals.
- The *evaluation* of characterisation, simulation, and design results should include a **multi-scale** strategy to relate small-scale experiments with large-scale design and prototyping. In the same way, a **digital-physical** comparison should be included to prove the **safety** and **reliability** of the system.

Figure 1.2

Research areas and objectives.



The integrative structural design methodology and workflow should include aspects of all four research areas. Details on each process's parameters and possibilities should also be given to structural designers as guidance to ultimately prove the structural safety of the building system.

1.3 Exclusions

Although the integrative structural design methodology is developed to aim for the design of any non-standard building system, the work is only demonstrated by its application in coreless filament-wound (CFW) structures as a case study. This structural system constitutes an excellent non-standard building system example as it can showcase the interaction of non-standard geometry, material system and fabrication technique, which requires the integration of all research objectives into the structural design workflow.

However, this dissertation's strategies and workflow generalisation should be tested and proven with other non-standard building systems to understand the adaptation that each different system might need. The discussion and outlook presented in Chapter 5 give initial hints on how the methodology could be modified considering the non-standard factors presented in different systems.

2. Background

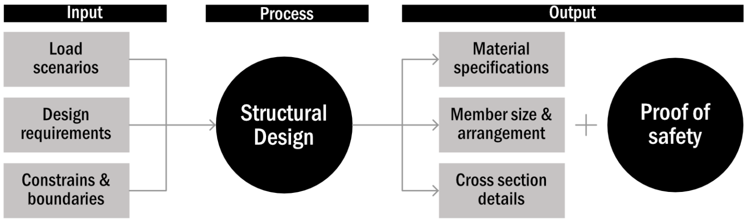


Figure 2.1

Structural design definition with inputs and outputs.

Structural design is the engineering process of designing the structure to safely resist the applied forces and load effects in the most resource-effective and efficient manner. Aspects of design which are not an explicit part of the strength consideration are also implied in this process, such as sustainability, constructability, and usability (Anwar & Najam 2017). The design process connects formal architectural ideas of geometrical form to a structural system (Kloft 2005), and it provides a unique response to the specific requirements and scenarios of each project (Bollinger et al. 2008).

Figure 2.1 illustrates structural design as a process with inputs and outputs. Load scenarios, design requirements, constraints, and boundaries are the necessary inputs for the structural design process. Then, two primary key outputs should be produced. The first consists of a description of what has to be built: material specifications, member size and arrangement, and cross-section details. The second is a justification of the design proposal that has been made, the proof of safety (Addis 2003). Therefore, structural design is the process in which the output, along with material and design specifications, must include the necessary degree of confidence in the proposed structure: the confidence to begin building (Addis 2016).

It should be noted that engineers had designed and constructed buildings, bridges, and other structures with considerable skills and success long before advanced structural simulations or design codes were developed. Progress in engineering has been made by carefully analysing and predicting the causes of failure, independently of the method, which was either physical, mathematical or simply the strength of experience (Addis 2016). Then, the material design and structural system were adjusted to prevent the predicted type of failure.

Therefore, it is then essential to look into structural design history and understand how engineers have faced the challenge of designing new structural systems, which at that time were above standards but resulted in successful outcomes. History reveals how different technological advancements have influenced the construction sector and the creation of new structures, frequently also linked to the development of new materials or the society's needs.

2.1 Historical overview of the structural design evolution

The construction and building methods have evolved in parallel with the historical advancement of technologies and the development of new materials. The availability of local sources, influenced by climate, land, and local skills, was also crucial for the type of structures that could be built. The methods employed to use the first construction materials, such as stone, mud or timber, grew out from countless experiments and accidents, creating an experience that was transferred generation by generation (Ngowi et al. 2005).

In the Middle Ages, the terms engineering or structural design were still not defined, and in Europe, guilds managed construction for all the building development (Ngowi et al. 2005). The historical separation of fields did not arrive until the Renaissance, differentiating professional designers and contractors. In the seventeenth century, designers first began to think about the load-bearing aspects of buildings regarding their weight, materials and structure. However, thinking separately about structure and material was only introduced after Galileo's work in the late-seventeenth and eighteenth centuries (Addis 2003). The specialisation of other engineering fields was linked to the increment in knowledge in the nineteenth century, during the industrial revolution (Veer 2016).

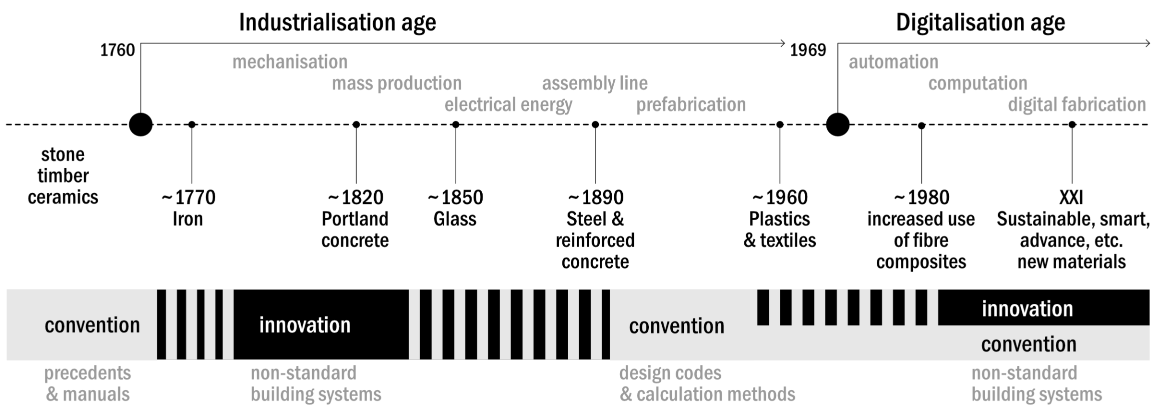


Figure 2.2

Simplified overview of historical key aspects for the development of structural design.

Even though ancient times also taught us valuable lessons on the evolution of construction and the means to build, the industrialisation and the differentiation of design roles during this time allow us to understand the influencing factors and evolution of structural design. Figure 2.2 illustrates key historical aspects that contributed to the development of new structures and their structural design. The figure is meant to simplify the complexity of a period, from 1760 to the present day, when multiple events had different levels of repercussion on the construction industry. The discovery of **new materials** and the introduction of **technical advancements** are two major contributors to change and are the focus of the diagram.

The period represented can be divided into *industrialisation*, when mechanisation, mass production, electrical energy, assembly lines and later prefabrication appeared, and *digitalisation*, which includes automation, computation, and digital fabrication. Again, this division simplifies a much more complex historical overview, deeply researched by other authors such as (Scheuermann et al. 2015), (Klinc & Turk 2019), (Alaloul et al. 2020), or (Begić & Galić 2021), where it is distinguished between Industry 1.0 to 4.0. This classification, although not entirely necessary for the scope of this dissertation, is interesting as it further subdivides the presented *industrialisation age* and *digitalisation age* periods shown in Figure 2.2, including the following technological events:

Industrialisation age:

- **Industry 1.0**: Mechanisation, steam power, weaving loom.
- **Industry 2.0**: Mass production, assembly line, electrical energy.

Digitalisation age:

- **Industry 3.0**: Automation, computers and electronics.
- **Industry 4.0**: Robotics, cyber-physical systems, artificial intelligence, big data, internet-of-things, network.

The development of new materials is another critical factor that occurs parallel to technological progress. In the *industrialisation age*, iron, glass, and steel enabled the construction of larger infrastructures and building frames (Ngowi et al. 2005). Then, Portland concrete and later reinforced concrete were rapidly spread in the construction industry, creating new architectural forms. Finally, plastics and textiles were introduced, enabling novel tensile structures. The *digitalisation age* witnessed the slow increase in the use of fibre composites and the development of a significant amount of new materials; more sustainable, smart or high performative. Many of these are not linked to the invention of the material itself but to improving the manufacturing processes, making it accessible and more economical for construction applications.

Consequently, both novel materials and fabrication techniques are a direct opportunity and challenge for the engineers who have to design and prove unconventional systems without additional precedents. In this way, this historical period can be seen as an iterative transition between innovation and convention. Innovation is always linked to the appearance of non-standard building systems and convention to developing guidance, design codes and calculation methods. The introduction of innovation was more abrupt in the industrialisation age as no strong conventions were set. In the digitalisation age, there is great potential for innovation, but new structural design methods are necessary to convince and prove the systems' safety as very well-established conventions already exist.

The following sections of this chapter look into historical events representing these two periods, the primary key aspects and developments, and their influence on structural design.

2.2 The industrialisation age – Innovative structural design

The *industrialisation age* is a stage of rapid change in history, which affected most areas of our society, including the construction sector. The large number of building materials resulting from the industrial revolution, coupled with the continuously increasing demand for new housing in Europe after each of the World Wars, resulted in the *industrialisation of construction*. This process is considered as the change from traditional labour methods to modern ones, resulting in more efficient construction technologies (Ngowi et al. 2005). The improved technical possibilities of production also allowed new geometries in architecture (Kloft 2005).

Different development periods linked to innovation in structural design can be spotted. The first period began with the introduction of iron at the end of the eighteenth century and comprised the rise of new forms directly connected to the use of new materials to solve the transport problems caused by industrialisation (Billington 1985). The second period corresponds with the end of the nineteenth century and is linked with the drop in steel prices and the development of reinforced concrete. The early search for forms with concrete broke with previous geometrical conceptions. Some authors talk of *"structural art"* for the new line of projects that followed the ideals of efficiency, economy and elegance (Billington 1985). The third period includes developments in plastics and textiles that enabled new tensile structures, looking into structural efficiency through experimental physical models.

2.2.1 Iron and lightweight

The introduction of iron at the end of the eighteenth century was one of the essential milestones in construction history. Iron is much heavier than the previously used materials, as it is three times denser than stone and seven times more than timber (Addis 2003). Therefore, the search for *minimum-weight structures* became an essential design factor for the first time in history, as the material weight is directly related to its cost.

The second crucial structural design aspect from this period is the adjustment of the structure to the material characteristics. An example of how engineers achieved this design conception can be seen with three bridges, illustrated in Figures 2.3, 2.4 and 2.5. The *Iron Bridge* of the Serven River (Figure 2.3) was the first cast-iron structure. Its arched design resembles earlier designs in wood, not taking the full potential of the new material. However, as the strength of iron is about five times that of wood, one-fifth of the material was necessary to carry the same loads. Therefore, the bridge design was much less solid, a fact that saved it from a disastrous flood, becoming an inspiration and motivation to other engineers to use iron (Billington 1985). The *Craigellachie Bridge* over the River Spey by Thomas Telford (Figure 2.4) constitutes the oldest surviving bridge where modern metal forms were used. The X-braced and radial struts that connect the bridge arches are proof of this. The *Menai Bridge* over Menai Straits (Figure 2.5), also by Thomas Telford, represents the longest-spanning structure in the world when completed. It is designed with wrought-iron suspension chains (Billington 1985). This bridge shows another example of innovative structural design inspired by the new material.

It is noteworthy that it was not easy for engineers like Thomas Telford to gain confidence in their designs. Many projects were rejected, and some of them failed. The engineers kept monitoring each of their projects, often being able to reinforce part of the structure before failure. Together

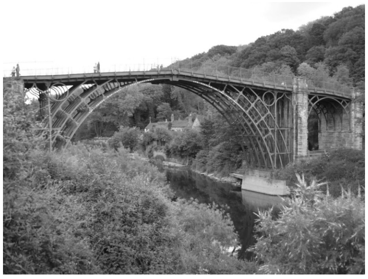


Figure 2.3

The Iron Bridge across the Severn River, Coalbrookdale, England, 1779 by Abraham Darby (Parksy 2005). The first major structure ever built of iron. It still presents the form and details of earlier non-metal arches.

Figure 2.4

The Craigellachie Bridge over the River Spey, Elgin, Scotland, 1814 by Thomas Telford (Pixabay 2017). The oldest surviving bridge representing the first modern metal bridge forms.

Figure 2.5

Menai Bridge over Menai Straits, Wales, 1826 by Thomas Telford (Fox 2010). Wrought-iron chain-suspension bridge, the longest-spanning structure in the world when completed.

Figure 2.6

Stauffacher Bridge in Zurich, Switcherland, 1899, by Robert Maillart (Хрюша 2011). His first bridge based on traditional stone bridges.

Figure 2.7

Salginatobel Bridge near Schiers, Switzerland, 1930, by Robert Maillart (Rama 2008). The form of the bridge is designed by graphic statics in response to the self-weight of the bridge.

Figure 2.8

Tempul Aqueduct over the river Guadalete, Jerez de la Frontera, Spain, 1927, by Eduardo Torroja (Unknown 1927). First prestressed concrete bridge, a precursor to modern cable-stayed and extradosed bridges.

with the development of theories, calculations and engineering intuition, each finding made early iron engineers push the boundaries of the structure, achieving larger spans and lighter structures.

2.2.2 Concrete and form

The structural design of concrete structures also had a transformation period vital for structural design. Like iron with wood, early concrete buildings mimicked iron- and steel-framed or even stone buildings until designers soon realised the potential of the material's *form-finding* qualities. The refinement of form depends on a conceptual and mathematical understanding of the structure to be designed (Pedreschi 2008).

The first new forms were developed by the Swiss engineer Robert Maillart. In his first work, the *Stauffacher Bridge* (Figure 2.6), the form is designed based on traditional stone bridges. However, a remarkable evolution in his designs is noticeable when looking at the most highlighted of his bridges, the *Salginabotel Bridge* (Figure 2.7). This bridge is designed with a three-hinged arch, and its form is manipulated to control the cross-section stiffness (Pedreschi 2008). He was also responsible for developing new structural typologies in concrete, including the *column-supported floor*, the *beam-supported roof*, and the *thin-shell vault* (Billington 1985).

Another important engineer worth mentioning in the early development of concrete design concepts was Eduardo Torroja, a Spanish engineering professor and designer. In his work at the *Tempul Aqueduct* (Figure 2.8), Torroja demonstrated outstanding innovation and courage by proposing the first prestressed concrete bridge, a precursor to modern cable-stayed bridges. He only used hand calculations based on material strength equations and minimised the material uncertainties by monitoring the built structure during its fabrication (Lozano-Galant & Paya-Zaforteza 2017).

Afterwards, several lines of development occurred in Germany, Italy, and Spain. The common goal, investigated through different strategies, was to cover large areas with curved concrete surfaces and create strong structures with thin, curved slabs rather than thick, flat ones. This concept was the beginning of *the search for form*, summed to *the search for lightweight.* In the *Zarzuela Hippodrome Roof* (Figure 2.9), Torroja showed how the identity of form and structure previously achieved by masonry could be realised with thin concrete vaults. The roof shell cantilevers with a thickness on the outer edge of only 50mm, achieving an extraordinary light appearance. A full-scale test of one roof section was made, proving that it could carry three times its design load (Billington 1985). Later, Felix Candela succeeded in creating a new style of shells that matched the material's performance. The roof of his *restaurant at Xochimilco* (Figure 2.10) was composed of eight hyperbolic paraboloidal vaults with only 41 mm thickness that were arranged on a circular ground plan. Candela experimented form and lightness with numerous projects in Mexico, as the current regulations there were more flexible for building non-standard structures. His work inspired other great engineers who followed, achieving spectacular concrete structures, such as Heinz Isler. Ten years after the Xochimilco restaurant, Isler showed a deep understanding of the nature of concrete and thin solutions (Kloft 2005). His work in the *Deitingen Service Station* (Figure 2.11) demonstrates his techniques effectively. He utilised the catenary principle, using experiments with suspended fabric scale models to support his designs (Pedreschi 2008).

Figure 2.9

Zarzuela Hippodrome Roof near Madrid, Spain, 1935, by Eduardo Torroja (unknown 1935). A 12.8-meter cantilever thin concrete shell.

Figure 2.10

Restaurant Los Manantiales, Xochimilco, Mexico, 1958, by Felix Candela (Dge 2016). Hyperbolic vault roof where structure and form are one.

2.2.3 Tensile structures and efficiency

The developments in *lightweight design* and *form-inspired structures* did not finish with concrete. As the knowledge in structural design increased and new materials were developed, more architects and engineers were encouraged to innovate.

The introduction of tensile structures overlaps with the previous period, as early works can include the *Dorton Arena* by Matthew Nowicki and Fred Severud in 1952 (Figure 2.12). This building constitutes the first cable-supported roof system and separates the utilisation of materials to resist different forces in the building: concrete to handle the compression and steel cables to resist tension. Severud and Nowicki's work in the Dorton Arena is also an excellent example of early integrative structural design. They used the concept of structural form to drive the architectural design in an integrative design approach, achieving an important design breakthrough (Sprague 2013). This project greatly influenced future tensile structures, including Frei Otto's work.

Figure 2.11

Highway service area Deitingen south, Solothurn, Switzerland, 1968, by Heinz Isler (Хрюша 2009). Two symmetrical freeform concrete shells.

Frei Otto's famous soap film experiments helped design the principles of minimal surface applied to membranes (Nerdinger 2005). These forms were designed through a model-based form-finding process that was structurally optimised following the rules of physic (Kloft 2005). The *Olympic Stadium* for the 1972 Munich Olympic Games (Fig-

Figure 2.12

Dorton Arena during construction, North Carolina, United States, 1952 (Brazilian National Archives 1952), by Matthew Nowicki and Fred Severud. The first cable-supported roof system.

Figure 2.13

The Olympic Stadium for the 1972 Munich Olympic Games, Germany (Royan 2007), by Frei Otto. The culmination of his work.

ure 2.13) is considered the culmination of his research. The project is also the largest of his work, covering a total of 75000 square meters using over 210 kilometres of cable (Royan 2007).

The work of Frei Otto was particularly influential in the development of modern membrane structures. However, tensile membranes' full potential was not unlocked until the use of computers and computational form-finding methods that utilise geometric-nonlinear techniques (Bradshaw et al. 2002).

2.3 From innovation to convention – The standardisation process

Standardisation can be defined as the process of articulating and implementing technical knowledge. If this knowledge is successfully implemented, it creates an authoritative and trusted standard. This process has taken place in history in almost every imaginable way, politics, business, economics, science, technology, labour, culture and ideas (Russell 2005). *Standardisation* can be recognised in three different areas in construction and structural design: materials and fabrication processes, structural systems, and design methodologies.

With the *standardisation of materials and fabrication processes*, the construction industry could produce more, faster and cheaper. In contrast to these economic benefits, the prefabrication of construction elements devalued skilled workers in the 1930s (Russell 2005). The *standardisation of structural systems* constitutes the change from innovation to convention in structural design, creating typologies that can be easily repeated and calculated. Finally, the *standardisation of design methods* relates to the development of design guidance in the form of manuals and codes of design practice.

2.3.1 Structural typologies

Structural typologies are a categorisation of the unique relationship between the form of a structure and the related load-bearing behaviour (Saldana Ochoa et al. 2021). Early classification of typologies is given by Heino Engel (Engel 1968).

In the *experimental structural design* of the beginning of the industrial age, new structures were created without the guidance of typologies, as no fixed conventions existed yet. The threshold for the standardisation of structural systems can be considered to occur at the beginning of the nineteenth century. An example of this change can be seen in the design of greenhouses, which were one of the first applications of iron and glass frames. In the case of the Bicton Garden's greenhouse (Figure 2.14), the roof is designed using iron and glass without material hierarchy (Knippers 2017), just inspired by the need for light inside the building. About 25 years later, in the greenhouses of Kew Gardens (Figure 2.15), a hierarchic arrangement of the materials and the arches as primary and secondary beams can be already recognised (Knippers 2017). Afterwards, the new structural typology was used repeatedly in large stations and exhibition halls.

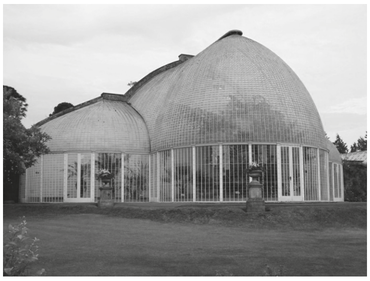


Figure 2.14

Greenhouse of Bicton Garden, United Kingdom, 1818 by John Claudius Loudon (Platt 2010). Glass and iron without material hierarchy.

Figure 2.15

Palm house of Kew Gardens, United Kingdom, 1848 by Reginald Turner (Case 2014). The beginning of frame hierarchy.

2.3.2 Manuals and structural design codes

The earliest *design rules* that can be found are for building and civil engineering structures from Classical Greek times. These documents gave guidance but did not tell the designer

what to do, requiring considerable experience for its use (Addis 2016).
The realisation of *manuals* for the design of structures as a precedent to current design codes goes back to the eighteenth century, especially for timber construction design (Yeomans 1987). These manuals included tables with simple formulas to establish the dimensions of timber components for floors or roof structures. The formulas contained empirical constants with no scientific significance. However, there was no intention or attempt to justify these dimensions as they were well-established (Addis 2003).

In order to standardise the design process and address the variability and uncertainty in loads and materials, *structural design codes* were developed from the late nineteenth century onward (Teichgräber et al. 2022). They provide design data, criteria and calculation procedures to help engineers ensure safety and check stability of civil and engineering structures (Addis 2016). They cover loading, types of structures, and load-bearing materials.

2.4 The digitalisation age – Integrative structural design

The introduction of digital technologies into industry characterises the *digitalisation age*. After the increasing successful interaction of computer science with the fields of electrical, mechanical and control engineering, the concept of computer integrated manufacturing was also introduced in 1973. With this, the new terms of computer-aided design (CAD), computer-aided engineering (CAE) and computer-aided manufacturing (CAM) were created (Menges 2015b).

In architecture and structural design, its influence was not specifically substantial in the first years, as the technological developments brought by digitalisation were focused on the digital control and automation of already established manufacturing processes.

It was only in recent years, coinciding with the *Fourth Industrial Revolution*, that the impact on building design and construction practices became exponential. These developments allow the production of very complex forms that were difficult and expensive to design, produce, and assemble using traditional construction technologies (Kolarevic 2001). The *Fourth Industrial Revolution* does not aim to increase productivity but rather flexibility, adaptability, and integration, which might significantly impact architecture (Menges 2015b).

In engineering, the developments in computation, materials, and digital fabrication also constitute an opportunity for integrating and realising novel structural designs. Computational design has allowed the integration of the structural behaviour in a parametric environment, involving optimisation in early design stages. Developments in new materials, and the way of using them, open the possibility of break with previously established structural typologies. This new way of thinking materiality is complemented by the *cyber-physical process* that digital fabrication enables, unveiling further material explorations. As a result, computational design, engineering and construction should be integrated with these processes in a flexible, iterative, and agile way (Knippers et al. 2021).

The following sections give an overview of the aspects concerning engineering that have been introduced by computational design, digital fabrication, materiality, and the current search for sustainability. These topics are interrelated and overlapped rather than separated. Besides, the amount of state-of-the-art new systems that combine different computational techniques, materials and fabrication methods is countless and not the scope of this background. Nevertheless, the following overview shows the variety of non-standard systems that the digitalisation age is producing, in which the structural design and proof of safety are not yet entirely solved and need to be addressed in the coming years.

2.4.1 Computational design and parametric optimisation

The impact of *computation* on the perception and realisation of forms, space and structure is becoming profound (Menges & Ahlquist 2011). Digitally driven design processes allow for dynamic and open-ended three-dimensional geometrical transformations, producing new architectonic possibilities (Kolarevic 2004). 3-D modelling allows for innovation not only in architecture but also in the field of computational mechanics and simulation technologies, offering opportunities to develop new structural forms (Knippers 2013).
Several recent projects with complex geometries demand novel approaches to structural design and engineering, in which *performance-based design* and *digital workflow* are closely related (Kloft 2005). Data integration between different disciplines and data postprocessing methods for structural feedback that automate and accelerate iterative exchange are becoming essential (Kloft 2005). Parametric design strategies are also an opportunity for structural

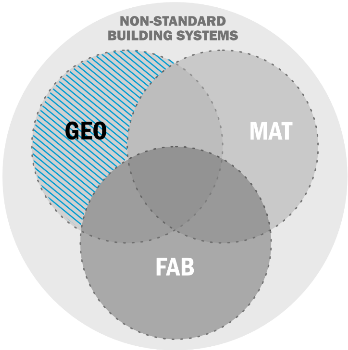


Figure 2.16

BMW Welt, Munich, Germany, 2007 (Delso 2013). An example of parametric structural design in an integrated digital design workflow (right) and its classification as non-standard building system (top).

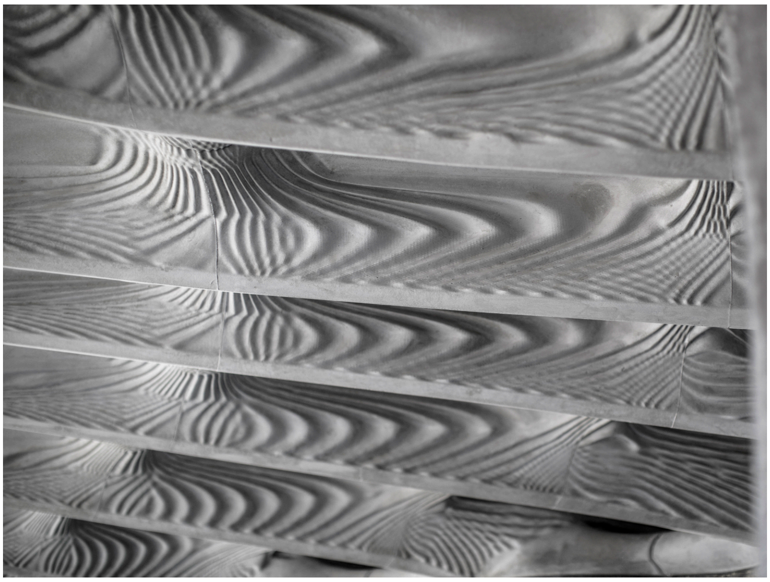
design. In fact, strategies to integrate structural assessment on parametric models for early design fast feedback are already being introduced in design workflows (Preisinger & Heimrath 2014)

As an example, the roof of the *BMW Welt* in Munich (Figure 2.16) was designed in a collaborative process using computational design and multi-parametric structural design. With the geometric complexity of this building, any change in its elements had repercussions on the global system. Consequently, an integrative design approach with intense collaboration and data exchange was crucial (Bollinger et al. 2008).

2.4.2 Digital fabrication and the cyber-physical process

Influenced by the design thinking from the Renaissance, in computation, the design processes and the manufacturing of those designs remained conceptually separated. In recent years, designers are beginning to realise the importance of the relationship between the computational domain and the physical realm. Therefore, computation is beginning to be used as a vital interface for material exploration in a *cyber-physical process* which includes new modes of *digital fabrication and manufacturing* (Menges 2015a).

Smart slab (Figure 2.17), designed by researchers at ETH Zurich, represents an example of using digital manufacturing to modify and improve an existing structural system, a concrete slab. The digital fabrication methodology allows for material optimisation using the flexibility of a 3D printed formwork and structural simulation to create hierarchical



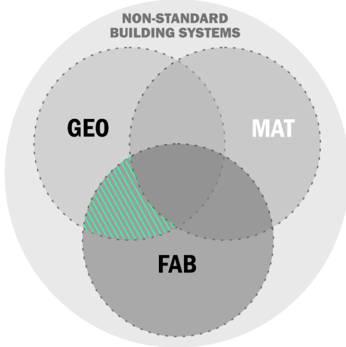


Figure 2.17

"Digital Concrete", ETH Zürich, Switzerland (Jipa 2018). An example of using digital fabrication combined with structural optimisation (left) and its classification as non-standard building system (top).

ribs on a 20 mm thick concrete shell. The prestressed concrete elements are prefabricated, and the resulting slab achieved a 70% material reduction compared to conventional concrete slabs. The integrative design in this project utilised a simplified 2D FEA model to evaluate and optimise the position of the ribs based on several performance criteria. Additional aesthetic constraints are added to the simulation to generate a performative freeform that also responds to other needs, such as the space's acoustics (Meibodi et al. 2018).

2.4.3 Materiality and the opportunity to move beyond typologies

There is also a great opportunity of using *materiality and material behaviour* as a design factor instead of form. Combined with the significant amount of materials being developed nowadays, this direction opens up multiple possibilities to break with conventional structural typologies. By embedding physical properties and material behaviours in computational design, the architectural and structural design processes are also challenged (Fleischmann et al. 2012). Therefore, digital design workflows need to be adjusted.

The research by the Institute for Computational Design (ICD) and the Institute of Building Structures and Structural Design (ITKE) on elastic bending developed since 2010 is an excellent example of how material behaviour can be used to enable novel computational design processes. This research direction developed the so-called *bending-active systems*, which resulted in versatile, complex and structurally effective structures (Fleischmann et al. 2012). *One Ocean*

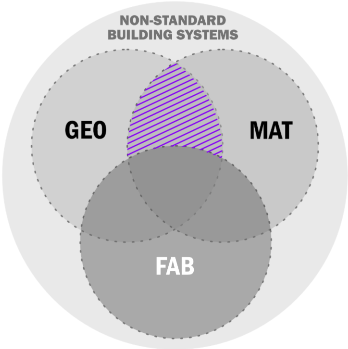


Figure 2.18

One Ocean Thematic Pavilion Expo Yeosu 2012, South Korea, by soma architecture and Knippers Helbig Adcanced Engineering (Fildhuth 2012). An example of material behaviour as a design driver (right) and its classification as non-standard building system (top).

Thematic Pavilion at the EXPO 2012 in Yeosu, South Korea (Figure 2.18) is the first kinetic façade that works based on elastic bending. The individual lamellas of the façade are fabricated with glass fibre-polymer composites and are deformed by controlled buckling, allowing to adapt the internal space to desire light conditions (Lienhard et al. 2013). This structural system breaks with any previous preconceived typology utilising the material's properties as the driving design factor.

2.4.4 Digital technologies and the search for sustainability

The increasing demand for new buildings due to rapid urbanisation and, in parallel, environmental challenges produced by CO2 emissions and pollution have led to a search for sustainability in the construction sector. Quality models and assessment processes are being developed (Zhang et al. 2020) combined with computational design and digital manufacturing techniques. Besides, new digital technologies are unlocking the introduction in the construction sector of novel material systems, or the reinvention of already used materials in a more sustainable way. The non-standard structures created by these methods bring the potential towards more sustainable architecture but frequently constitute also an engineering challenge since these materials are harder to characterise.

An example can be found with the *eco-sustainable 3D printed habitat, TECLA* (Figure 2.19) in Massa Lombarda, Italy, which was completed in 2021 by WASP and Mario Cucinella Architects (Chiusoli 2021). It represents a new circu-

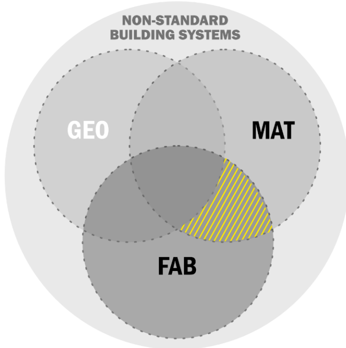


Figure 2.19

Eco-sustainable 3D printed house "Tecla", Massa Lombarda, Italy (WASP 2021). An example of digital technologies and sustainable solutions (left) and its classification as non-standard building system (top).

lar model of housing entirely created with reusable and recyclable materials, sourced from local soil, carbon-neutral and adapted to any climate and context. The project was entirely 3D printed with multiple printers operating simultaneously. The house is designed with a double dome solution, merging geometry and structure, and using digital fabrication to take a basic material, such as raw earth, to its physical limit. The project follows the principles of circular economy and sustainability (Chiusoli 2021).

2.5 Coreless filament-wound structures as a non-standard building system

*Fibre-polymer composites (*FPC) in architecture have been used since the 1950s (Bank 2006). However, in contrast to other construction materials, such as steel or concrete, its development did not occur immediately. This delay can be justified due to the available calculation techniques for fibre composites, which at that time only provided the means to prove safety to continuous laminate structures, limiting their use or development (Knippers 2017).

The Classical Lamination Theory (CLT) considers a stack of unidirectional layers combined to produce a stiffness matrix for the laminate, equivalent to an anisotropic plate (Bert 1989). Due to this reason, the calculation method does not allow adaptation of the fibre orientation to the load direction, which restricts the material potential. Besides, only fabrication techniques such as hand layup, filament-winding, or pultrusion could produce this type of continuous plate. Due to cut-offs or mould materials, these techniques often produced a significant amount of waste. Consequently, FPC

Figure 2.20

Monsanto Plastics Home of the Future, California, United States, 1957 (Orange County Archives 1958), an example of modular prefabricated FPC in the 1950s.

Figure 2.21

ICD/ITKE Research Pavilion 2012. The development of new materiality for fibre-polymer composites: Coreless filament winding @ICD/ITKE University of Stuttgart.

applications were mainly modular structures in which it was possible to re-use the mould multiple times, as in the case of the *Monsanto House of the Future* in 1957 (Figure 2.20), fabricated by modules of FPC (Knippers 2017). It was only after 2012, with the development of *coreless filament winding* (CFW), that different *materiality* in composite structures could be appreciated, where the fibre filaments are aligned with the stress flow through a project-specific fabrication-oriented design (Figure 2.21).

Coreless filament winding was developed at the University of Stuttgart through the collaborative research between ICD (Professor Achim Menges) and ITKE (Professor Jan Knippers). This alternative approach aimed to reduce the mould of state-of-the-art filament winding to minimise the waste materials produced during fabrication (La Magna et al. 2016). Since then, computational design in-

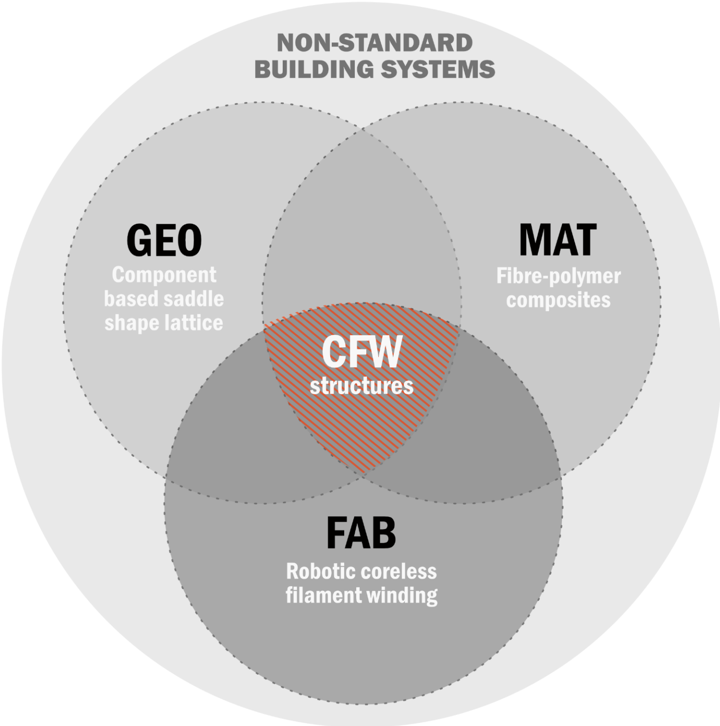


Figure 2.22

CFW structures as a non-standard building system.

spired by biomimetic principles and integrated with engineering methods and fabrication feedback has unveiled unexpected and inspiring *materiality* (Menges & Knippers 2015).

Just as it happened historically with iron and concrete, digital technologies have now helped overcome limitations and allowed the utilisation of the full potential of fibre composites. The resulting CFW structures constitute a novel non-standard system which can be situated at the intersection of non-standard fabrication, material, and geometry (Figure 2.22).

2.5.1 Robotic fabrication technique

Coreless filament winding is a robotic fabrication technique that utilises light and discrete steel frames with anchor pins to provide the boundaries for filament winding, resulting in lattice lightweight structures. A typical fabrication setup for CFW (Figure 2.23) consists of an industrial, six-axis robot arm, a resin bath, a spool holder, a custom-built end effector and the frames or supports for winding (Dambrosio et al. 2019). These can be stationary or mounted on external axes or manipulators. The configuration of the setup and the included elements directly impact the fabrication solution space that can be tailored to generate different component types (Gil Pérez et al. 2022a).

During fabrication, the robot pulls the fibres through the resin bath for impregnation. The robot then winds the

Figure 2.23

CFW typical robotic fabrication setup @ICD/ITKE University of Stuttgart.

wet fibres from anchor to anchor, following a planned robotic path called *syntax* (Zechmeister et al. 2019). The syntax is repeated, creating fibre interaction until the designed material amount is reached. After the component completion, it should be cured in an oven at a high temperature for a specific time, depending on the resin specifications. The curing process allows the composite to reach its final mechanical properties, at which moment the frame can be removed.

2.5.2 Material system and design

The fibre-polymer composite *material system* used in CFW can vary depending on the fibres and resin system chosen. The fibres are used as continuous filaments or yarns (Figure 2.24) supplied in spools. Each of the roving in the spool contains thousands of filaments (the exact number depends on the product specifications), which are then impregnated with resin during fabrication.

The resulting *unidirectional* composite bundle presents highly anisotropic properties that are a function of the composite's fibre volume ratio (FVR). The longitudinal direction has much higher stiffness and strength values than the transverse direction. The *anisotropy ratio* (as the ratio of the axial to transverse properties) varies with the type of fibre (Harris 1999). For example, high-performance fibres, such as carbon fibres, can have an anisotropy ratio of about 10, while this ratio is much lower in natural fibres. Other factors, such as possible defects in the fibres, might result in variability of the final mechanical properties. For CFW, it is essential to understand the properties and possible devi-

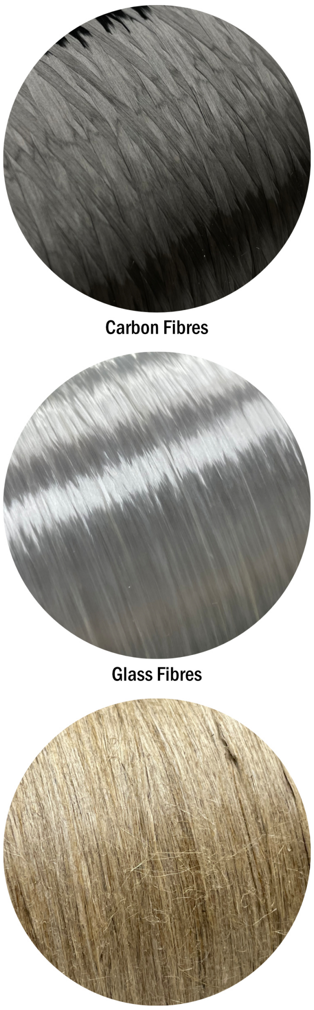


Figure 2.24

Fibre materials used in CFW built projects: carbon, glass and flax fibres.

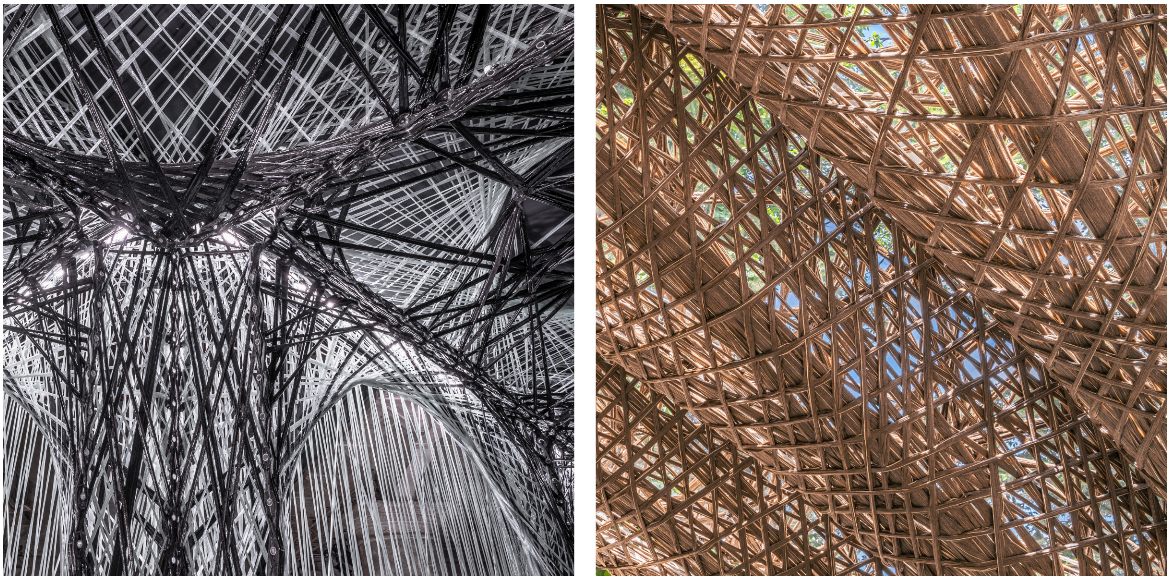


Figure 2.25

Materiality of a carbon/glass fibre component compared to a flax fibre component.

ations of the system chosen, whether technical or natural fibres, to adjust the design to the material behaviour.

Most of the built CFW projects utilise a combination of glass and carbon fibres impregnated with epoxy resin. For this configuration, the glass fibres are placed firstly with a regular pattern that creates a lattice surface. The glass fibres, being more economical, are used for this lattice with the minimum material amount to produce enough support for winding the carbon fibres on top, creating fibre interaction. The carbon fibre reinforcement layer, having a much higher strength than the glass fibre lattice, is considered the load-bearing structure of the components and the material is placed tailored to the load distribution. Other beneficial properties that carbon fibre composites can provide are high strength-to-weight ratio, low thermal expansion, and high fatigue and corrosion resistance (Fitzer 1985).

Recent projects have also investigated the change of the composite material system to more sustainable ones, such as flax fibres or bio-based epoxy resins. With the flexibility that CFW provides, the design can be adjusted from a more discrete to a more homogeneous fibre arrangement creating a very different aesthetics (Figure 2.25). The orientation of each fibre bundle individually in space for each of the layers blurs the boundary between material and structure, shifting the design scope towards *"designable materiality"* (Menges & Knippers 2015).

Therefore, for the design of these structures, an integrative approach is necessary, where computational design, simulation methods and fabrication feedback are incorporated into a digital-physical workflow. Different methods and design approaches have been explored, and since 2019, the

Figure 2.26

Overview of CFW projects between 2012 to 2017. From left to right: ICD/ITKE Research Pavilion 2012, ICD/ITKE Research Pavilion 2013-14, ICD/ITKE Research Pavilion 2014-15, Elytra Pavilion 2016, and ICD/ITKE Research Pavilion 2016-17 @ICD/ITKE University of Stuttgart.

Excellence Cluster Integrative Computational Design and Construction for Architecture (IntCDC) has aimed to develop and unify the methods into a *multidisciplinary co-design approach* (Knippers et al. 2021).

2.5.3 Demonstrating the system: Overview of first built projects

Since 2012, several pavilions and building demonstrators (Figure 2.26) have been used to investigate the architectural and structural possibilities of CFW building systems. Although other topics related to digital fabrication and design were also explored, this section only highlights the most relevant engineering aspects investigated.

The *ICD/ITKE Research Pavilion 2012* explored two essential areas: the digital simulation of the fibre interaction during the manufacturing process and the discretisation of carbon and glass fibres to achieve different stiffness gradients by using surface models with different material matrices (Waimer et al. 2013)(Reichert et al. 2014). Other monolithic structures were also researched by developing different fabrication setups and winding configurations, as in the case of the *ICD/ITKE Research Pavilions 2014-15* (Schieber et al. 2015) and *2016-17* (Solly et al. 2019).

In the *ICD/ITKE Research Pavilion 2013/2014*, a modular system was introduced with the design of one of the most representative component types in CFW, which became the inspiration for many of the following modular projects. The component comprises two opposite edges spatially connected by continuous wound fibres that create a *saddle lattice surface* (Dörstelmann et al. 2014).

An important milestone after this project was the development of the *Elytra Pavilion in 2016*, which evolved from the 2013-14 pavilion and was fabricated for the Victoria and Albert Museum in London, UK (Prado et al. 2017). The components followed the same logic but with a simplified fabrication, as they kept a regular geometry (unifying the winding frames) with a customised fibre layup that responded to the load levels. For the structural design, the component's lattice grid was modelled using a beam-element FE approach that described the fibre bundles, while the entire pavilion's global geometry was represented by surface elements (Koslowski et al. 2017).

This project constituted the first step to transfer the system from research to the industry and marked the beginning of a second research phase, where *proving structural safety* became one of the most significant engineering research aspects.

2.5.4 From research to practice: the current research directions

From 2019 until 2021, three CFW projects have been developed and built (Figure 2.27) with very diverse research objectives, ranging from *performative long-span* to *hybrid building systems* and *sustainable structures.* These projects are included in this dissertation to develop the presented integrative structural design methods, as shown in Chapter 3.

The *BUGA Fibre Pavilion* aimed to cover a larger span than previous projects with a dome-liked structure. Previous modular projects are the inspiration for the component's design, but in this case, the winding frames are separated in space, creating a bone-liked shape (Dambrosio et al. 2019).

Maison Fibre corresponds with the development of the first fibre-timber hybrid components, used as slabs in a multi-storey building system application. The material combination into a hybrid system in which both materials are structurally performative was the most novel aspect of this

Figure 2.27

Overview of CFW projects built between 2019 to 2021. From left to right, up to down: The BUGA Fibre Pavilion, Maison Fibre and LivMatS Pavilion @ICD/ITKE/IntCDC University of Stuttgart.

project, together with the actual application; a CFW structure became *walkable* for the first time (Dambrosio et al. 2021).

The *LivMatS Pavilion* explored the design possibilities of a new material system: flax fibre composites, which was previously not used in any CFW application. The design is adapted to the material needs, aiming to explore more sustainable architecture (Gil Pérez et al. 2022b).

Although these projects seek different global objectives, the three share common engineering challenges, which are addressed in this dissertation. Changes in the syntax in which the component is wound can produce changes in the geometry. Besides, the fibre bundle's cross-section can vary with parameters such as the component curvature or the *winding resolution* (number of rovings used versus passes in the layup). These variations and uncertainties are not fully defined until the final design is determined. In addition, the composite material also deviates. For example, differences in tension during winding can result in an uneven distribution of FVR along the bundles. Therefore, the structure's mechanical properties are unknown and need to be investigated during the design phase.

Given all these uncertainties, and without conventional methods that can represent the system, *the proof of safety* in CFW structures is an engineering challenge that so far has only been handled on a case-by-case basis.

2.6 Structural design tools to prove safety

The *capacity* of a structure is relative to a specific load scenario and a specific set of mechanical properties to determine whether it can or cannot carry the loads. The *proof of safety* of a structure is, therefore, relative to the engineer's decisions on material strength and loading. It is the *engineer's judgment* to decide whether the methods, hypothesis and results to prove safety are realistic enough (Ditlevsen & Madsen 1996).

Nowadays, with standard building systems, *safety factors* ensure that variations in the load or material properties constitute a small risk. However, as non-standard systems keep emerging, these safety factors are not always applicable, or higher factors are assumed to ensure the structure's safety and reliability. Looking back into history one can realise how safety was proved in the past when there were insufficient mathematical methods and codes that defined safety.

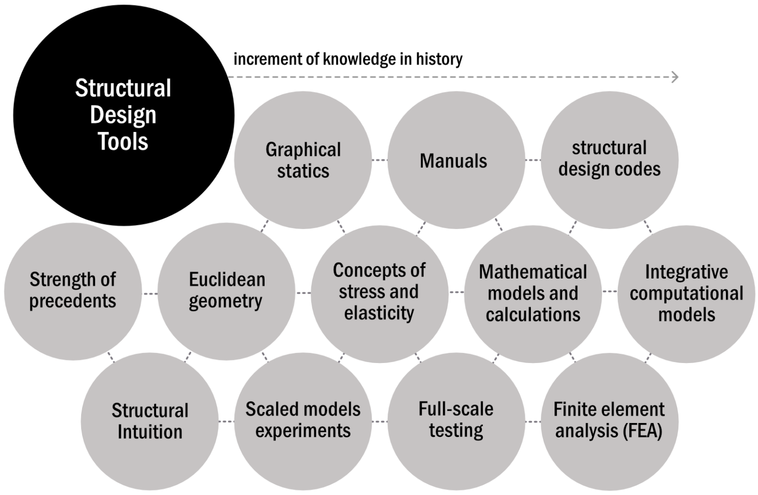


Figure 2.28

Structural design tools to prove safety in structural design linked to the increment of knowledge in history.

Figure 2.28 gives an overview of the most commonly used methods to prove safety in history. These methods are not developed linearly nor always used as a single strategy. Nevertheless, a relationship is kept between the *knowledge level* and the development of new ways of proving safety. It should also be considered that the engineer's judgement is the only thing that has never changed in history. The engineers in the past, like nowadays, decided which available tools to use, how their models were set, and which loading conditions they assumed.

The most powerful method still used nowadays is *the strength of precedents*. Even when no other tool existed, many structures were just built by copying examples that were already successful. This conceptually followed *inductive logic*, a logic of evidential support, such as the level of confidence can increase as a certain method is repeated with successful use (Addis 2016).

Perhaps, it should also be questioned how different engineers in the past perceived the gap between what they knew that was already built and what they believed possible. This gap can be called *structural intuition*. John Mainstone described three forms of structural intuition that were used to design structures empirically based on experience and observation in the nineteenth century (Mainstone 1973):

- *Intuitions of structural behaviour*: a spatial sense of the actions of force and stability
- *Intuitions of structural action*: more precise ideas of force, moment and equilibrium
- *Intuitions of structural adequacy*: a perception of the adequacy of a generic structural form for a particular application

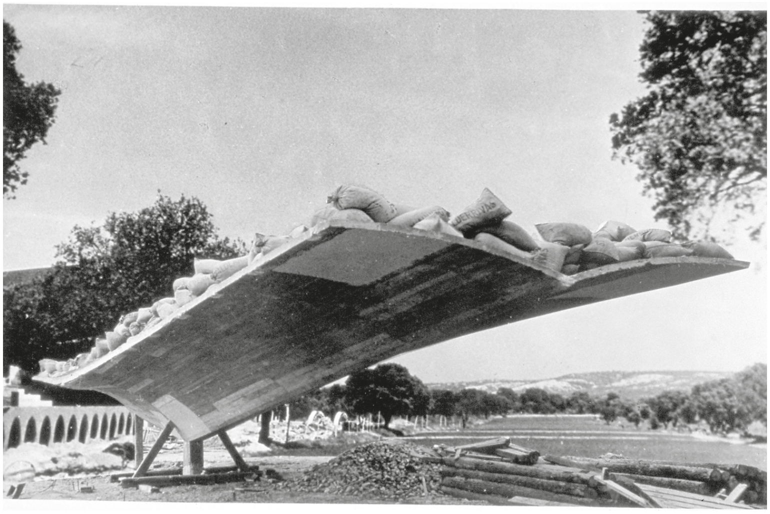


Figure 2.29

Load test of the Zarzuela Hippodrome roof by Eduardo Torroja (Archivo Torroja - CEHOPU-CEDEX 1935).

One of the oldest mathematical forms of justification is *geometry*. During the twelfth and thirteenth centuries, the changes and innovations in the design of cathedrals are attributed to the rediscovery of *Euclid's book on geometry* (Addis 2003). The sudden increase in geometrical knowledge supplied the Middle Age builders with the means of justification to construct higher cathedrals with thinner walls and larger openings. This design revolution coincided with the pass from *Romanesque* to *Gothic* and was not linked to any new material or fabrication device, just to the *increased confidence to begin building* (Addis 2003).

In the eighteen century, the design of the structures began to be based on *theories* and *scaled physical models*, reducing the need to rely only on experience (Teichgräber et al. 2022). However, *concepts of stress and elasticity* were not introduced until the nineteenth century, along with the first cast iron applications (Addis 2016). The introduction of *structural analysis methods* followed in the second half of the nineteenth century, establishing the *paradigm of calculability*; if a structure cannot be calculated, it cannot be built (Knippers 2013).

The development of *graphical statics* in 1866 by Karl Culmann constituted another significant step in the proof of safety methods. It is based on the graphic representation of the force in a structure, both in magnitude and direction (Pedreschi 2008). Many engineers relied upon this method as the primary form of proof. For example, the bridge of Malliart in Figure 2.7 was designed using mainly graphic statics. Only in the second half of the twentieth century the graphic statics method was superseded by computer numeric procedures (Bollinger et al. 2008).

As the knowledge increased, more *mathematical models and calculations* appeared. At the beginning of the twen-

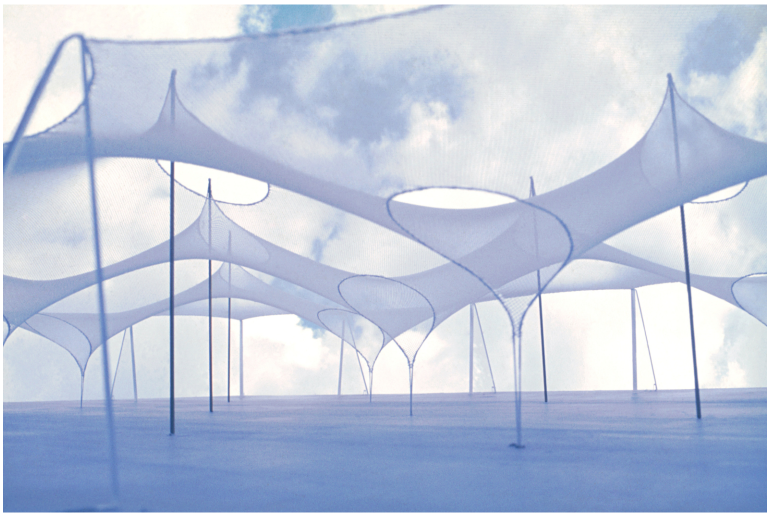


Figure 2.30

Frei Otto form-finding scaled models (Otto 1967).

tieth century, *general theories* and *analytical methods* already monopolised the way of designing and proving safety (Bollinger et al. 2008). However, when it came to innovative non-standard structural systems such as the Zarzuela Hippodrome roof by Eduardo Torroja, other means to prove safety were still necessary, and *full-scale structural testing* was frequently performed in partial full-scale structures (Figure 2.29). Besides, *scaled models* were also used to explore materiality and discover inspiring building forms, such as the form-finding models of Frei Otto (Figure 2.30).

Advanced design simulations arrived in the 1970s with the *Finite Element Analysis (FEA)*, allowing the reliable calculation of highly statically undetermined structures and non-linear behaviour (Knippers 2017). By including these simulation methods in digital and integrative design workflows, structural feedback can be used as a design driver. In combination with the current *design codes*, which are based on the semi-probabilistic partial safety factor concept (Teichgräber et al. 2022), structures are designed and documented with great details of justification.

Ironically, this sophisticated, well-established simulation and standards combined methodology can make it challenging to develop structural design innovations that cannot be modelled or are not described in these codes. It is the task of new engineers to be creative and find ways to break through conventions, providing ways to build the new generation of non-standard building systems.

3. Publications

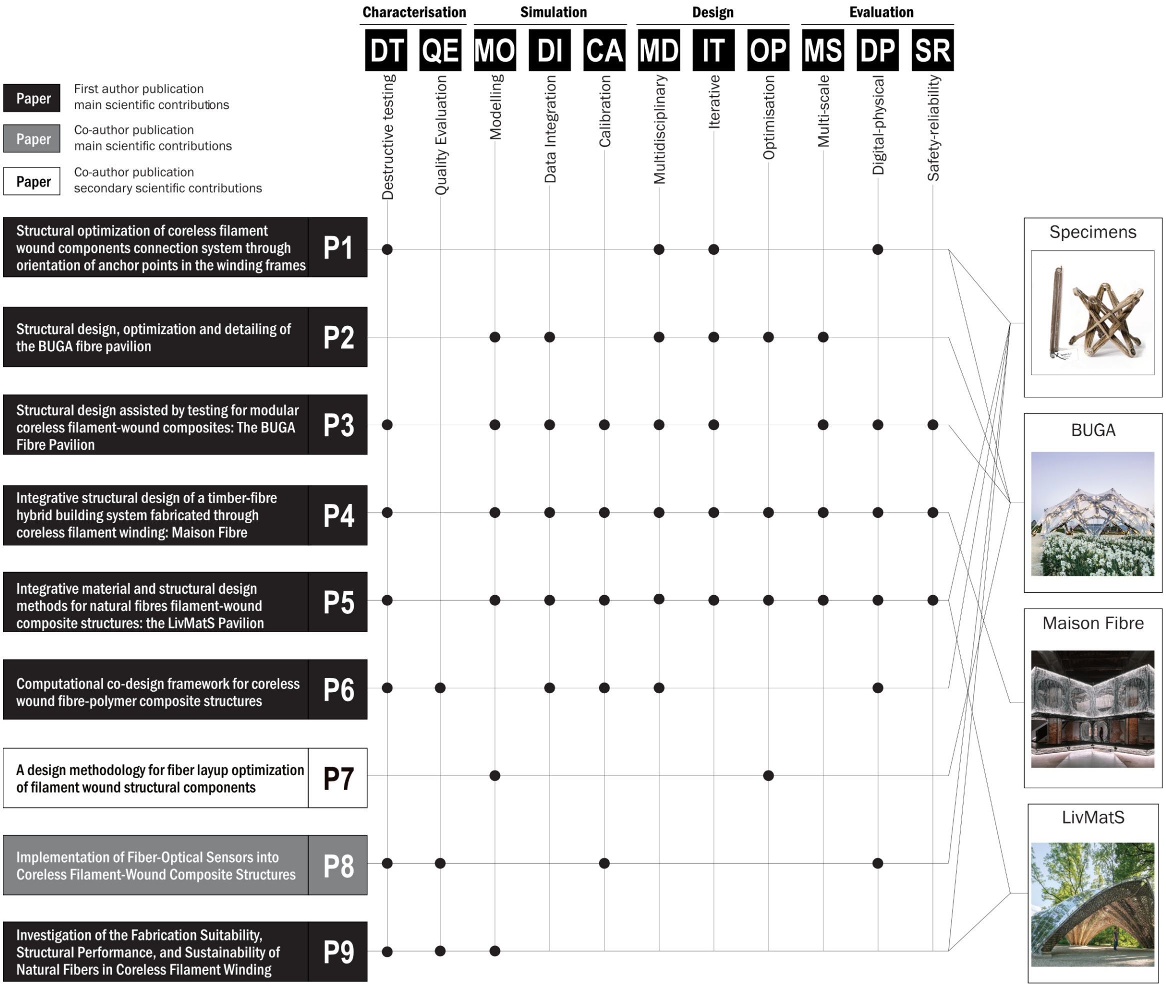


Figure 3.1

Presented publications overview linked to research objectives and demonstrators.

This chapter includes the manuscripts in their original published form. The work is presented and showcased using CFW specimens or one of the following built projects: The *BUGA Fibre Pavilion*, *Maison Fibre* or *LivMatS Pavilion*. Figure 3.1 describes the contribution of each paper to the research areas and objectives, as well as the associated physical demonstrator. As it can be seen, the content of publications **P3**, **P4**, and **P5** present the more significant contribution, as they describe the complete **integrative structural design** methods and workflow for CFW structures. The rest of the publications contribute to developing and giving details on the different methodologies summarised in Chapter 4.

3.1 Structural optimization of coreless filament wound components connection system through orientation of anchor points in the winding frames

Year: 2019
Authors: Gil Pérez, M.; Dambrosio, N.; Rongen, B.; Menges, A.; Knippers, J.
Proceedings: IASS Annual Symposium 2019, 1381-1388
URL: https://www.ingentaconnect.com/content/iass/piass/2019/00002019/00000006/art00023

This paper describes the design process assisted by structural testing followed to conceptualise the connection system of the BUGA Fibre Pavilion.

In previous research pavilions, the direction of the fibres in the proximity of the anchor points was mainly dictated by fabrication constraints, such as the geometry of the winding frame. In this study, the winding frame was modified to align the fibres to the load direction, taking full advantage of the anisotropy of the material. The designed specimens kept the characteristics of CFW structures with a simplified geometry to fit the testing machine. Using FEM, the fibre bundles were dimensioned to avoid the specimen's buckling failure.

A total of three iterations were designed and tested, with different modifications in the frame and location of the winding pins. The first design represented a direct connection (anchor to anchor bolted connection) between specimens but included the characteristic kinks produced by the imprint of the frame around the anchor area. A steel L-connector was designed to mitigate this problem. In the second iteration, this connector was implemented by turning the location of the winding pin to the frame side. In the third iteration, the connector and frame angle were adapted to the direction of the specimen fibres. The structural test showed a significant improvement in the load induction capacity. Therefore, the strategy was implemented in the BUGA Fibre pavilion by developing a computational tool that customised the frame edge of the specimens to match the expected direction of the wound fibres. The steel connectors were also designed following this angle discretisation and installed in their specific location during assembly.

The author contributed significantly to conceptualising the connection system, designing the testing setup, performing and evaluating the structural testing, and designing and dimensioning the final connectors.

Characterisation
Destructive testing DT
Quality Evaluation QE
Simulation
Modelling MO
Data Integration DI
Calibration CA
Design
Multidisciplinary MD
Iterative IT
Optimisation OP
Evaluation
Multi-scale MS
Digital-physical DP
Safety-reliability SR

3.2 Structural design, optimization and detailing of the BUGA fibre pavilion

Year: 2020
Authors: Gil Pérez, M., Rongen, B., Koslowski, V., Knippers, J.
Journal: International Journal of Space Structures, 35(4), 147-159
DOI: https://doi.org/10.1177/0956059920961778

This article describes the structural design of the BUGA Fibre Pavilion, focusing on global design modelling and structural behaviour, geometrical optimisation, and detailing of the dome.

Unconventional materials and structural systems usually need a more exhaustive FE analysis with parallel models to prove the integrity of the design. The BUGA Fibre pavilion dome comprises hollow bone-like components connected at their nodes and covered by an ETFE membrane. The loads are transferred from the membrane into the structure through steel poles at these intersection nodes. A multi-level strategy is adopted to simplify the modelling and interpret the results. This strategy simplifies the global geometry by utilising simple beam elements representing the composite components. Then, the components are further detailed in local models where all the fibre layup is represented. An additional buckling sensitivity analysis was performed to prove the validity of the simplified global model.

The paper describes the dome's loading and primary structural behaviour, including the worst-case scenarios produced by wind loads. For the geometry optimisation, both fabrication and structural parameters were considered. The maximum connection forces were reduced by 27% and the geometrical deviations by 62%, clustering the geometries by groups and simplifying fabrication. This optimisation was achieved by minimising the bending moments in the out-of-plane direction, corresponding with the smaller lever arm of the components. Finally, the connection interfaces design and detailing are also explained in this article: from the component to component connection design, the membrane poles that connect to the membrane, and including the foundation design. The structural design of the pavilion shows the importance of multidisciplinary design and iterative evaluations between different levels of modelling.

The author significantly contributed to conceptualising the design workflow and the structural optimisation, analysing and interpreting the results from the FEM, and designing and dimensioning the details.

3.3 Structural design assisted by testing for modular coreless filament-wound composites: The BUGA Fibre Pavilion

Year: 2021
Authors: Gil Pérez, M., Rongen, B., Koslowski, V., Knippers, J.
Journal: Construction and Building Materials, 301, 124303
DOI: https://doi.org/10.1016/j.conbuildmat.2021.124303

This article focuses on the description of the BUGA Fibre Pavilion component structural design, including the FE modelling strategy, fibre layup explorations and the full-scale structural testing scheme to verify and validate the component's structural capacity.

The design of CFW composite components requires an iterative and multidisciplinary strategy. The global-component FE analysis is of great importance for this pavilion as the component needs to be designed for complex loading scenarios. As the global design and assumptions are updated, the component maximum forces and moments used for the design need to be also updated; therefore, a strategy is needed for the data transfer to maintain these models separated. The paper describes the most important global design iterations and how these were used and influenced the component design.

For the fibre layup, several investigations also took place at different levels of definition. The first consisted of a rough evaluation of the possible layup patterns based on the syntax sift measured by the rotation angle between one frame and the other. Then, the selected option was further detailed and evaluated against buckling for each component's total loading cases. For the components which underperformed, the layup was adjusted.

The article also describes the complete full-scale structural testing scheme. A total of three components were tested for compression and bending moments. Besides, one test of a representative node was performed to prove the integrity of the connection areas. Additionally, all unique components were tested non-destructively under the design compression load. The results from the tests were used to calibrate the FE models and verify safety.

The author's contribution lies in conceptualising the workflow, modelling the components' FEM, creating the data transfer strategy between global and local models, designing the full-scale structural test and interpreting the results from both simulation and testing to verify the structural capacity and integrity of the system.

Characterisation
Destructive testing **DT**
Quality Evaluation **QE**

Simulation
Modelling **MO**
Data Integration **DI**
Calibration **CA**

Design
Multidisciplinary **MD**
Iterative **IT**
Optimisation **OP**

Evaluation
Multi-scale **MS**
Digital-physical **DP**
Safety-reliability **SR**

3.4 Integrative structural design of a timber-fibre hybrid building system fabricated through coreless filament winding: Maison Fibre

Year: 2022
Authors: Gil Pérez, M.; Früh, N.; La Magna, R.; Knippers, J.
Journal: Building Engineering, 49, 104114
DOI: https://doi.org/10.1016/j.jobe.2022.104114

This article describes the integrative structural design of the Maison Fibre, a timber-fibre hybrid building system. Especial emphasis is given to the design of the fibre layup and the structural testing and optimisation of the components.

Maison Fibre is the first timber-fibre hybrid structure and multi-storey building system with CFW components. Therefore, planning an integrative structural design scheme, including full-scale testing, was the primary research challenge in this project. The integrative design and fabrication process, as well as the multi-level modelling for structural assessment of CFW structures, are described. Several modelling strategies with different levels of definition are used at different stages of the design, alternating both surface and beam element models. This multi-level strategy is used to identify misleading results due to simplified models and assumptions taken at early design stages. For this reason, several modelling calibrations are included in the workflow, and the full-scale structural test results are used for the final calibration of the detailed models.

The fibre layup design was carried out through an integrative iterative process which included prototyping models and simulation. Each iteration was updated following both fabrication constraints and structural performance. The structural test was then designed to represent the most loaded conditions of the fibre layup, including connectors and connection areas. Four iterations of the structural test were performed, each evaluated in terms of structure and fabrication. The final iteration achieved a weight reduction of 15% compared to the first component tested. The calibrated FEM was then used to optimise the rest of the structure and further reduce the amount of material of less loaded components.

The author significantly contributed to conceptualising the structural design of the installation, the integrative design of the component's fibre layup, the design and performance of the structural tests, and the interpretation of results and optimisation of the components.

Characterisation
Destructive testing **DT**
Quality Evaluation **QE**

Simulation
Modelling **MO**
Data Integration **DI**
Calibration **CA**

Design
Multidisciplinary **MD**
Iterative **IT**
Optimisation **OP**

Evaluation
Multi-scale **MS**
Digital-physical **DP**
Safety-reliability **SR**

3.5 Integrative material and structural design methods for natural fibres filament-wound composite structures: the LivMatS Pavilion

Year: 2022
Authors: Gil Pérez, M.; Guo, Y.; Knippers, J.
Journal: Materials & Design, 217, 110624
DOI: https://doi.org/10.1016/j.matdes.2022.110624

This article focuses on integrating material testing methods into the structural design of the LivMatS Pavilion. The understanding of the implications of using natural fibres with CFW composite structures are analysed, and the design workflow and results obtained are described.

The LivMatS Pavilion is the first natural fibre CFW structure fabricated with flax fibres. The change of material from glass and carbon fibres used in previous projects was the real challenge of this project. The possible natural fibre materials were evaluated through research and testing for their use in the pavilion. Bio-based resins were also considered but resulted in worse mechanical performance and, therefore, could not be implemented in the large-scale structure. Nevertheless, the use of flax fibres with oil-based epoxy resin already constituted a significant step towards sustainable architecture.

Two different test setups were designed to represent the different failures found in larger CFW structures: buckling, delamination and fibre fracture. These tests served to choose the final material system and compare them with the full-scale structural testing. In parallel, the component fibre layup was designed using structural simulation with a multi-level modelling strategy. The global model provided maximum component forces that served as design loads for the component level. The fibre layup was optimised during the testing iterations, refining the design until a more homogeneous fibre lattice distribution was obtained, responding to the material needs. The fabrication variability and modifications needed during winding to implement the new material system greatly influenced the structural capacity and design choices. This publication describes the fabrication and structural implications and design iterations, emphasising the need for an integrative and iterative structural design.

The author significantly contributed to conceptualising the structural design workflow, the testing strategies, the fibre layup design and evaluation, and the material testing evaluation and design implications.

Characterisation
Destructive testing **DT**
Quality Evaluation **QE**

Simulation
Modelling **MO**
Data Integration **DI**
Calibration **CA**

Design
Multidisciplinary **MD**
Iterative **IT**
Optimisation **OP**

Evaluation
Multi-scale **MS**
Digital-physical **DP**
Safety-reliability **SR**

3.6 Computational co-design framework for coreless wound fibre-polymer composite structures

Year: 2022

Authors: Gil Pérez*[1], M.; Zechmeister*[1], C.; Kannenberg*[2], F.; Mindermann*[2], P.; Balangé, L.; Guo, Y.; Hügle, S.; Gienger, A.; Forster, D.; Bischoff, M.; Tarín, C.; Middendorf, P.; Schwieger, V.; Gresser, G.T.; Menges, A.; Knippers, J. (*[1] 1st author equal contribution, *[2] 2nd author equal contribution)

Journal: Computational Design and Engineering, 9(2), 310-329

DOI: https://doi.org/10.1093/jcde/qwab081

This article describes the development and application in a case study of a computational co-design framework for CFW composite structures. The focus is on describing the domain's interrelationships and multidisciplinary workflow to exchange and analyse data.

The success of large-scale CFW fibre composite structures for architectural applications relies on the reciprocal collaboration of simulation, fabrication, quality evaluation, and data integration domains. The correlation of data from those domains enables the optimisation of the design towards ideal performance and material efficiency. The computational co-design framework enables new modes of collaboration for CFW fibre–polymer composite structures.

The paper introduces a shared object model acting as a central data repository that facilitates interdisciplinary data exchange and the investigation of correlations between domains. The application of the developed computational co-design framework is demonstrated in a case study in which the data are successfully mapped, linked, and analysed across the different fields of expertise. This case study comprises three types of specimens. The geometries are 3-dimensional and have different levels of complexity, resembling CFW lattice structures. They are first simulated and then monitored during fabrication, scanned, and structurally tested with integrated fibre optical sensors. The results showcase the framework's potential to understand large-scale CFW structures and their fabrication and structural implications for design optimisation.

The author significantly contributed to the conceptualisation, methodology development and coordination of the work. Besides, the author also contributed to the specimens' design, structural testing, and analysis and evaluation of the results.

Characterisation
Destructive testing DT
Quality Evaluation QE
Simulation
Modelling MO
Data Integration DI
Calibration CA
Design
Multidisciplinary MD
Iterative IT
Optimisation OP
Evaluation
Multi-scale MS
Digital-physical DP
Safety-reliability SR

3.7 A design methodology for fiber layup optimization of filament wound structural components

Year: 2022
Authors: Guo, Y.; Gil Pérez, M.; Serhat, G.; Knippers, J.
Journal: Structures, 38, 1125-1136
DOI: https://doi.org/10.1016/j.istruc.2022.02.048

This article describes an alternative methodology to find optimum fibre layups for a given tube-shape geometry via a graphical optimisation strategy based on structural performance requirements. The methodology is benchmarked with the design and results of the BUGA Fibre Pavilion.

The complexities introduced by the material and fabrication processes in CFW make applying conventional simulation methods for the design of the fibre layup significantly challenging. By utilising classical lamination theory (CLT), it is possible to avoid explicit fibre layup modelling. These lamination parameters can generate a reduced stiffness matrix for continuous multi-layer fibre composite lamination. Therefore, the CFW component can be studied as a simplified laminate rather than as individual bundles modelled by beam elements. Miki's diagram provides the feasible design space to retrieve the optimal fibre angles and volume proportions for the layup based on the applied loading and design criteria.

This paper focuses on describing and applying the methodology to CFW structures. Modifications in the surface modelling and interpretation of results are also explained. The methods are then applied to one of the BUGA Fibre Pavilion components for benchmarking. The model and surface material properties are calibrated with the actual data from the performed full-scale structural test of the component. Then, a re-design of the component is performed using the methodology proposed under the compression-bending loads. The final design options achieved a better structural performance while reducing the necessary material amount required for the design. These results proved the potential of the proposed methods, which main advantage is not constraining the system with initial assumptions on the fibre layup but rather giving graphical guidance on the possible optimal designs.

The author contributed to the development of the conceptualisation and methodology, as well as the application of the methods into the benchmark case study, providing the original design analysis and testing data.

3.8 Implementation of Fiber-Optical Sensors into Coreless Filament-Wound Composite Structures

Year: 2022
Authors: Mindermann, P.; Gil Pérez, M.; Kamimura, N.; Knippers, J.; Gresser, G.T.
Journal: Composite Structures, 290, 115558
DOI: https://doi.org/10.1016/j.compstruct.2022.115558

This article describes methods for implementing fibre-optical sensors (FOS) in CFW structures. Besides, the interpretation and calibration of the structural data obtained by the sensors using FEA are also presented.

The fabrication method of CFW produces structures which frequently show significant structural deviations. Due to the level of uncertainty, relatively high safety factors must be applied to the design. The integration of FOS can provide an improved understanding of the structural behaviour, ultimately allowing the reduction of those factors. However, to fully utilise the capacity of the sensors, methods for its implementation, visualisation and interpretation are necessary as several factors, such as the location of the sensor within the bundle or the combination of axial forces and bending moments, can influence the raw data.

Several CFW specimens representing different geometrical configurations are used to demonstrate the FOS implementation and investigate the entire strain fields measured by the sensors in various load scenarios. The geometry of the specimens represents both lattice fibre bundle structures showing a significant number of intersections and the potential of the sensors and simple truss-like structures where the methods can be further detailed. The data obtained is visualised in their spatial contexts and analysed by FEM-assisted methods. The structural response was statistically described and compared with the ideal load distribution analysed with FEM to derive the actual load induction iteratively. This FEM-FOS comparison served not only to understand the FOS data but also to calibrate the FE simulations, reducing the gap between simulation and reality. The results prove the importance of sensor integration for monitoring and calibrating structural behaviour.

The author contributed to developing the data analysis methods, including the analysis and results for the quantitative analysis of FOS data using FEA, the calibration of FEA and the reduction of FOS deviations.

3.9 Investigation of the Fabrication Suitability, Structural Performance, and Sustainability of Natural Fibers in Coreless Filament Winding

Year: 2022

Authors: Mindermann*, P.; Gil Pérez*, M.; Knippers, J.; Gresser, G.T. (* 1st author equal contribution)

Journal: Materials, 15(9), 3260

DOI: https://doi.org/10.3390/ma15093260

This article explores a variety of alternative materials for their utilisation with the fabrication technique of CFW. The fabrication suitability, structural performance and sustainability aspects are analysed and evaluated.

The usage of natural fibres in the field of fibre-polymer composites is increasing to meet the growing demand for more sustainable structures. Natural fibres' production process (e.g., harvesting or fibre extraction) produces significant mechanical properties variability, frequently presenting a weak fibre-matrix interface linked to low reproducibility. The potential of these new material systems should be analysed considering their mechanical performance along with their sustainability aspects, and the material characterisation should be integrated into the design workflow. In terms of fabrication, the rovings must endure high tension during the winding. This challenge becomes exponential with natural fibres, as they present an insufficient strength when uncured. Therefore, adjustments in the fabrication process are also crucial.

In this work, a 4-point-bending test specimen is designed to evaluate and compare the structural performance of twelve different fibre types and two resin systems. In addition, a more complex specimen resembling a CFW lattice cylinder is also produced to evaluate the fabrication adjustments and suitability of the materials. The fibre-resin contribution is calculated to analyse sustainability indexes: embodied energy and global warming potential. Then, different comparisons are made, considering the literature data and the results obtained from the tests. The work shows the potential of several materials concerning lightweight solutions and sustainability aspects.

The author contributed significantly to the structural data postprocessing, statistical comparison, and interpretation of the results for both structural evaluation and sustainability markers.

4. Results

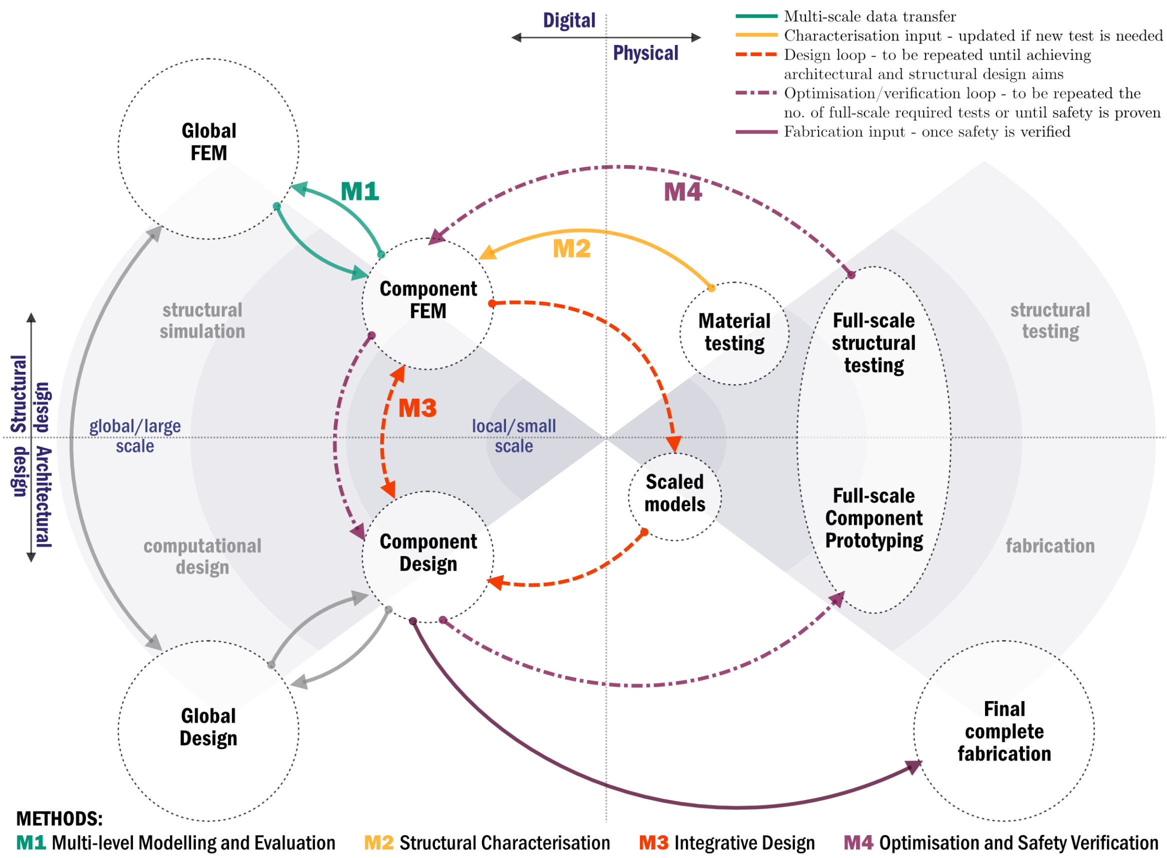
The main objective of the presented research was pursued through the structural design of coreless filament-wound structures as a case study. This chapter summarises and generalises the main findings according to the described research areas and objectives.

It is possible to extract the design workflow for non-structural building systems (Figure 4.1) from the developments accomplished in publications **P3**, **P4**, and **P5**, related to the integrative structural design of the *BUGA Fibre Pavilion, Maison Fibre,* and *LivMatS pavilion*, respectively. The rest of the publications partially contribute to explaining the methodologies that constitute the main workflow, as it will be described in the sections of this chapter.

Figure 4.1 illustrates the methods overview and integrative workflow. The design space is divided into *digital-physical realms* (left and right of the graphic) and *structure-design* (top and bottom). This division creates four quadrants corresponding to *structural simulation*, *computational*

Figure 4.1

Integrative structural design methodology and workflow overview.



design, *structural testing*, and *fabrication*. At the same time, a *multi-scale* approach is represented. Items closer to the central vertical axis are related to *local or small scales*, while the further ones to *global or large scale*.

Given this configuration, the necessary elements for the workflow are located. On the digital side, the *global design* and *global finite element model (FEM)*, as well as the *component design* and *component FEM* are located and interconnected, producing a multidisciplinary and multi-level modelling approach. This approach corresponds to the first methodology, **M1**, described in **Section 4.1, Multi-level Modelling and Evaluation**.

On the physical side, *prototyping* and *structural testing* at different scales are used in an iterative way to support and give feedback to the simulation scheme. In the first place, *material testing* is used to inform the local component FEM. The testing strategies are explained in methodology **M2**, described in **Section 4.2, Structural Characterisation**.

Then, the *first design loop* begins, involving the component design, component FEM and physical scaled models. This design loop is iteratively repeated until the architectural and structural design aims and requirements are achieved. Component design and component FEM are reciprocally informed to choose design options that fulfil structural performance and fabrication strategies and further investigate those with physical scaled models. This methodology, corresponding to **M3** in the graphics, is further elaborated in **Section 4.3, Integrative Design**.

Finally, when the design is ready for the final development stage where full-scale prototyping and testing can be involved, the last *optimisation and verification loop* is initiated. This loop needs to be repeated the same number as full-scale testing planned. More iterations will be necessary if proof of safety is not achieved, being the engineer responsible to judge the results and decide whether the structure is safe enough. From experience, a reasonable number of full-scale testing that can allow optimisation and verify structural safety should be no less than three iterations. Higher number of tests could be really costly for the project, while lower number would not give any certainty on the test deviations. The process and methods followed in this loop are described in **M4**, corresponding to **Section 4.4, Optimisation and Safety Verification**. At the end of this stage, the complete structure can be optimised using the simulation workflow, and the digital information is finally transferred for fabrication.

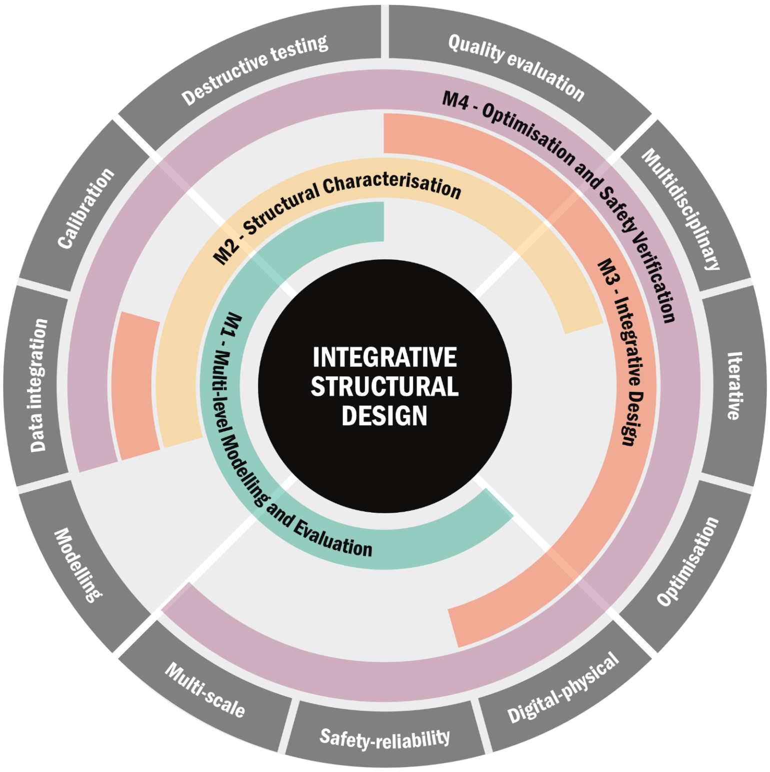


Figure 4.2

Integrative structural design methods and objectives achieved.

The methods or processes that compose the integrative structural design workflow achieved different objectives among the four research areas. The relationship between these methods and the research objectives is shown in Figure 4.2, and the following sections provide specific details and their relationship to the publications presented in Chapter 3.

4.1 Multi-level modelling and evaluation

Complex material systems frequently require alternative modelling approaches due to following two reasons. Firstly, the final design and mechanical properties highly depend on the geometry resulting from fabrication parameters. Secondly, the FE model should be refined according to the design process, evolving from a conceptual level to an advanced detail design level. A *multi-level FE approach* is flexible enough to allow the structure's assessment with different detail and refinement levels and from a dual global/component perspective.

In publications **P2**, **P3**, **P4**, and **P5**, **modelling** strategies and assumptions are given for CFW structures (Figure 4.3), while **P9** extends the information on material assumptions for alternative fibre material systems. The final geometry of CFW structures is unknown during the design process, making multiple levels of model refinement necessary. The load-bearing behaviour of CFW structures varies

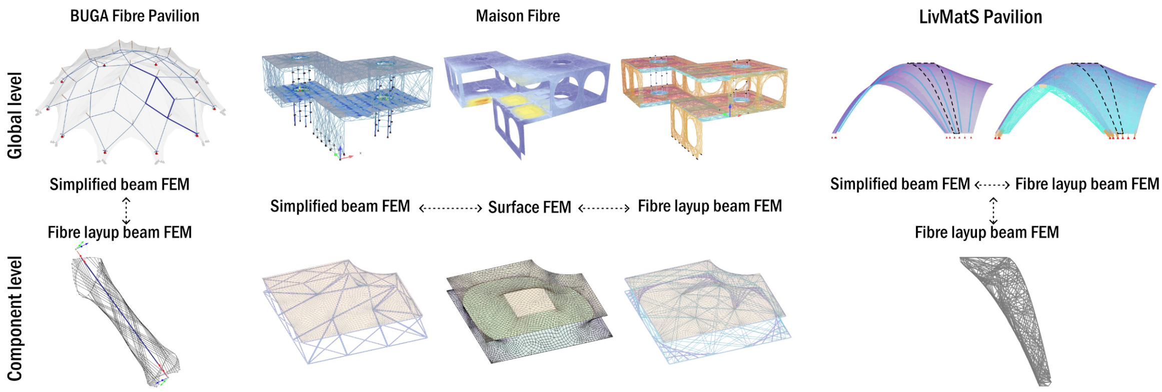


Figure 4.3

Multi-level modelling strategies.

from thin-walled surface components to truss components made of linear elements. Therefore, the overall behaviour is studied using a parallel approach with surface/shell models and beam models that represent the fibre placement and are used to dimension the fibre bundles. This approach helps designers use structural feedback during the design process, even in the early design stages, identifies misleading results by comparing various models, and a great modelling and computation time can be saved using these simplified representations. As shown in publication **P7,** this flexible simulation scheme allows other modelling strategies to be also integrated into the workflow.

In addition, *component-based systems* allow for a dual assessment, complementing the modelling strategy. A **multi-scale** approach, dividing global and component models, is also shown in publications **P2**, **P3**, **P4**, and **P5**. At the global level, the modelling can be simplified and include all loading conditions, while at the component level, the modelling can be more detailed, but the loading can be simplified. All of these methods require a strong strategy for **data integration**. Best examples of data integration between global-component are shown in **P3** and **P5**, while multi-level modelling data integration is demonstrated in **P2** and **P4**.

Evaluating the results is also essential, as unconventional modelling needs calibration and verification. **Calibration** of these models is achieved by comparing the different modelling approaches and the additional support of **destructive testing**. Then, a final **digital-physical** evaluation is required to validate the FE models and prove **safety and reliability**.

4.2 Structural characterisation

When using an unconventional fabrication method or material system, relying on material data of coupon tests manufactured differently is frequently unreliable or inexistent. Besides, existing testing methods might not represent the complexity of the building system and, therefore, customised designs to represent specific loading conditions are necessary. For example, in CFW, the resulting composite's mechanical properties and failure modes are strongly linked to the fabrication technique, the resulting geometrical shape, and the achieved fibre volume ratio (FVR) and compaction.

Suitable small-scale prototypes and **destructive testing** methods to characterise CFW structures and their joint systems (Figure 4.4) are described in publications **P1**, **P5**, **P6**, and **P9**. Each specimen type can be used at a different design stage to compare and find different results informing the process and **calibrating** the FE models. It is essential to differentiate which type of test and results are transferable to large scale design, as small-scale specimens do not always retain the same behaviour as the complete structural system. Partial testing or problem-specific experiments (as in publication **P5**) can be more effective than designing a coupon test to characterise all material properties.

The main advantage of including small-scale material testing during the design process is not only setting material properties but the possibility of reducing the need for full-scale testing. Another strategy with the same objective is the implementation of **quality evaluation** techniques such as *fibre optical sensors (FOS)* or *laser scanning* of the structure, as described in publications **P6** and **P8**. These techniques can improve the system reliability, making the design workflow more **multidisciplinary**, but require a more elaborated **data integration** approach, as shown specifically in **P6**.

Figure 4.4

Small-scale specimens designed to characterise CFW.

4.3 Integrative structural design

Non-standard building systems that do not follow conventional typologies, materials, or fabrication methods can benefit from a *digital design workflow.* **Optimisation** methods to reduce internal forces by adapting the form or geometry should be implemented from the early design stages to minimise the material usage of these structures. In order to utilize structural feedback during the design process, the structural design needs to be incorporated with an **iterative** and agile **data integration**. Establishing a solid and **multidisciplinary** design framework incorporating the different

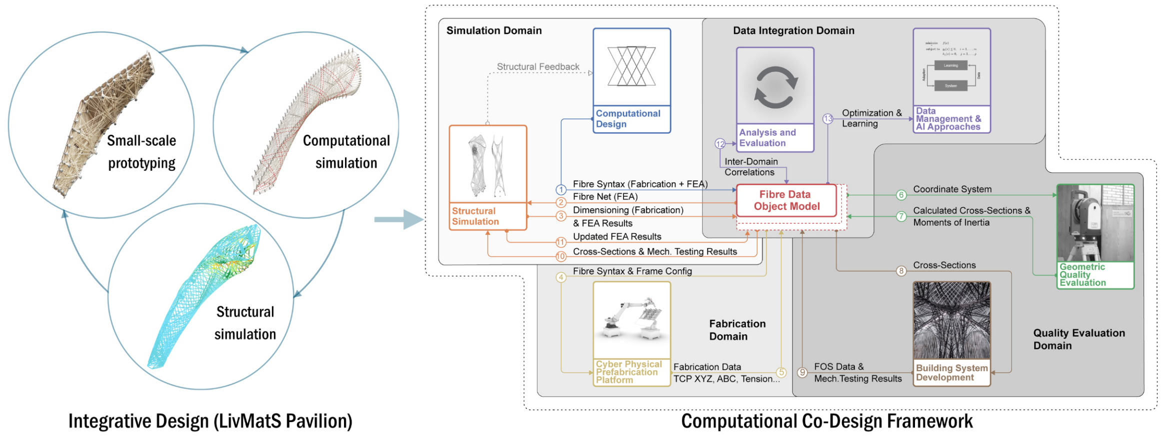


Figure 4.5

CFW structures integrative design future direction, towards computational co-design.

disciplines involved is crucial to efficiently producing valid design outcome. Besides, in systems where simulation cannot fully represent reality, a **digital-physical** design loop allows for checking fabrication and simulation parameters with physical scaled models. In the case of CFW structures, the *design*, *engineering* and *fabrication* involve constant assessment of requirements and parameters from all three aspects.

Publications **P3**, **P4**, and **P5** elaborate on the *integrative design* of modular fibre composite components for the *BUGA Fibre Pavilion, Maison Fibre* and *LivMatS pavilion*, respectively. In these three projects, the structural feedback is used **iteratively** with design and fabrication requirements showing successful results in the material usage **optimisation**.

Another example at a different scale of a **multidisciplinary** design that included **digital-physical iterative** feedback between structural, design and fabrication parameters is shown in publication **P1**. Here, the design of a suitable connection system for the *BUGA Fibre pavilion* is described, demonstrating that this approach is valid not only at a global scale but also at the detailing level.

The integrative structural design approach, shown in publications **P3**, **P4**, and **P5**, was extended into a **multidisciplinary** *framework* (Figure 4.5) in publication **P6** to improve the analysis and evaluation of the structural performance, as well as the **data integration** between disciplines. This framework includes in the design workflow the following methodologies: digital simulation, structural simulation, robot path planning, fabrication data capturing, laser scanning, structural monitoring with fibre optical sensors, structural testing, data and geometry mapping and optimisation and learning.

As can be seen, **quality evaluation** methodologies are also considered to inform fabrication and design. As a result, all these methods were successfully integrated into a complete *computational co-design framework* divided into *simulation*, *fabrication*, *quality evaluation* and *data integration* domains, with a central object model to store and exchange the data. The data acquired by the different domains is successfully mapped, linked, and analysed across the various fields of expertise. The *co-design framework* reveals novel interrelations and contributes to coreless filament wound structures' economic design and dimensioning. Besides, it also showcases new forms of collaboration that can be applied to the design of other non-standard building systems.

4.4 Optimisation and safety verification

The lack of structural codes and standardised simulation methods for new material and fabrication systems, such as CFW fibre-polymer composites, makes essential the validation of the structural **safety** and **reliability** through full-scale **destructive testing**. This experimental hands-on approach to design and construction is not as common in the building industry as in other engineering fields, where the primary design tool is based on prototypes and tests.

The design of the testing scheme needs to be planned carefully with a smart strategy to represent the worst-case scenario and build confidence in the design and structural system. Besides, the testing results can also be used for **calibration** of the FE models, unlocking further structural **optimisation** by using the already established **digital-physical** workflow. Similarly to the design loop, this optimisation and verification loop is also **iterative** and **multidisciplinary**, but the number of iterations needs to be based on the planned number of full-scale tests that can demonstrate safety.

The modular design of CFW structures enables the testing of single prototypes (Figure 4.6), which are then included in the overall design process as explained in publications **P3**, **P4** and **P5**. The tested components reassembled all fabrication and geometry conditions and were designed to represent the same load induction as the final structure, including connection systems and loading types. The FE analysis supports the decision of the component to be tested, and it is used during the whole process to evaluate the results. After **calibration** of these models, the comparison between internal forces in the testing FEM under the force the test withstood, and the internal forces in the global model under design loads allows for calculating the additional *safety margin* achieved.

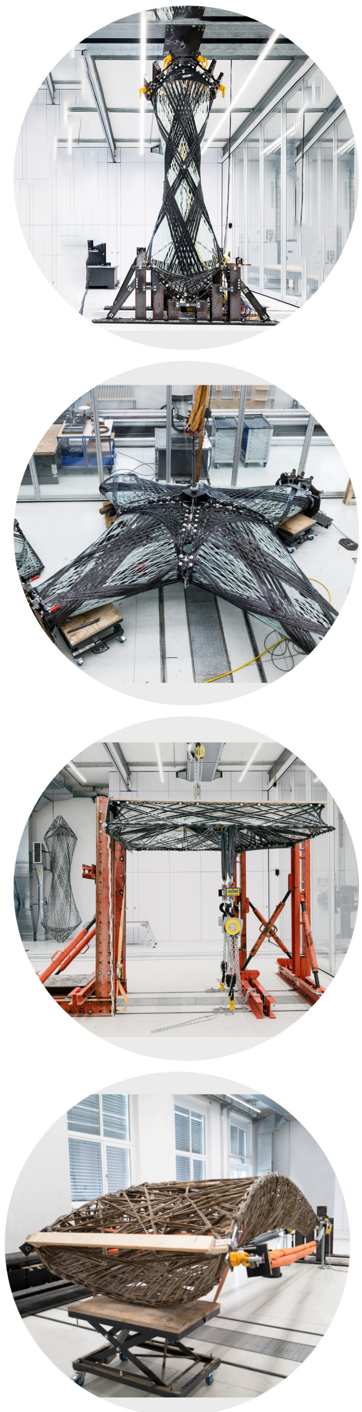


Figure 4.6

CFW full-scale structural tests.

The customised testing scheme can result in an additional cost for the project, which is sometimes impossible to afford. Due to this reason, other additional methods for **quality evaluation** or **structural characterisation** can be integrated into the workflow with the aim of reducing the amount of full-scale testing needed. In Publication **P5**, testing is performed in a **multi-scale** approach, where the full-scale test is supported and benchmarked with small-scale characterisation testing. Publication **P8** shows how *fibre optical sensors (FOS)* can be used to **calibrate** the FEM without the need for destructive testing. Moreover, publication **P6** elaborates on how these **quality evaluation** methods can be implemented during the design process, emphasising the importance of **data integration** techniques to achieve an efficient **multidisciplinary** workflow.

The *optimisation and verification methodology* described utilising prototyping, and full-scale structural testing enables the validation of innovative non-standard systems, building *confidence* in the design and shortening the gap between research and industry.

5. Discussion and Conclusion

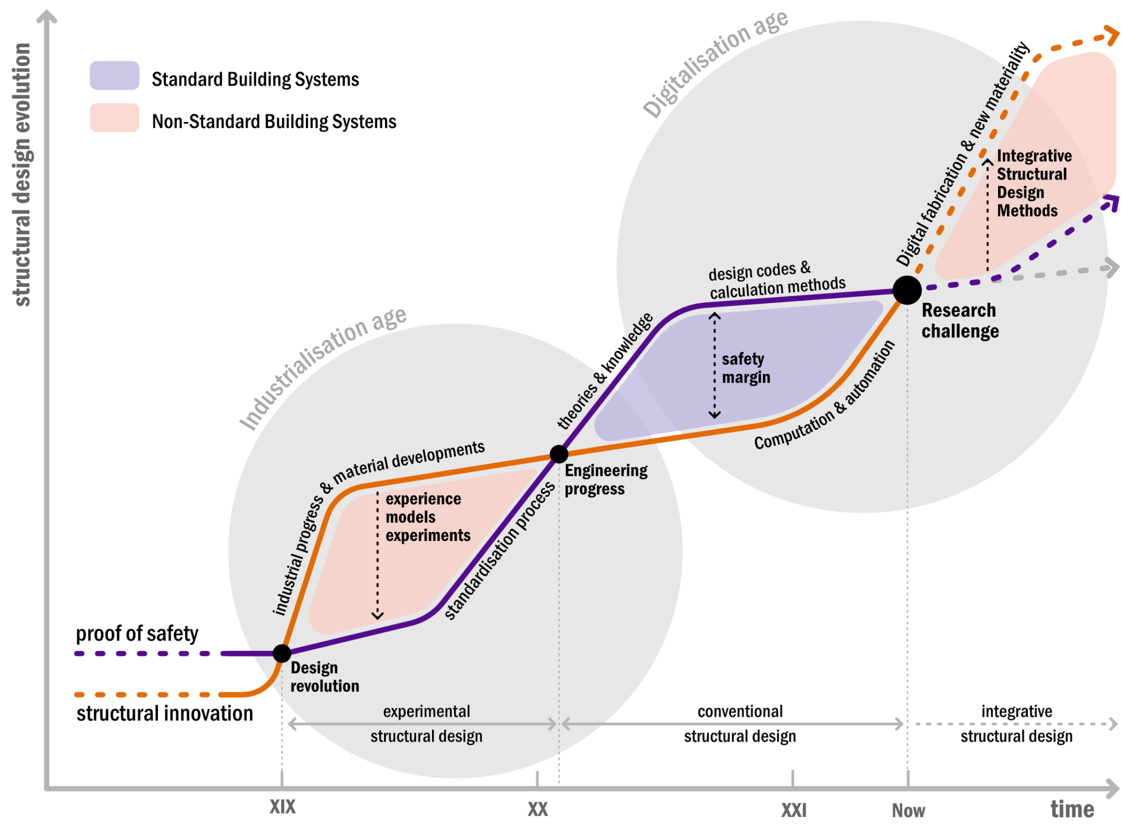
This dissertation presents an *integrative structural design* methodology and workflow for designing and validating non-standard building systems. Coreless filament-wound (CFW) structures are used as a case study to represent non-standard building systems as their geometry, material and fabrication are non-standard: the produced systems are component-based, robotically-fabricated fibre-polymer composites lattice structures.

The main developments of this research can be extracted from publications **P3**, **P4** and **P5**, as they are specifically dedicated to describing the integrative structural design of coreless filament-wound structures. The rest of the publications support the methods with further findings and details for the **characterisation**, **simulation**, **design** and **evaluation** of the structural system.

It is essential to understand where this new methodology fits in history. Figure 5.1 represents an interpretation

Figure 5.1

Conceptual evolution of structural design along history in relationship to the structural innovation and proof of safety developments, situating the current research challenge and aim of the integrative structural design methods.



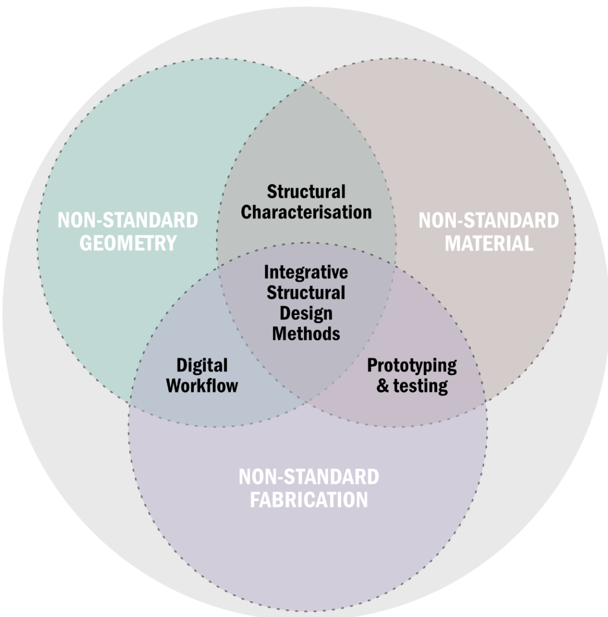
of the *evolution of structural design* in time as a combination of developments in *structural innovation* and *proof of safety*. The diagram also shows the two important periods described in Chapter 2, the *industrialisation age* and the *digitalisation age*. Industrial progress and material developments at the beginning of the industrialisation age produced a **design revolution** in which structural innovation evolved faster than the methods to prove safety. This period corresponded with non-standard building systems that required *experience*, *models* or *experiments* to be built.

The *standardisation process* soon helped to produce developments in the way safety was proven, which at a point, called in the diagram **engineering progress**, kept improving the methods with more *theories* and *knowledge*, moving above the slightly slower innovation evolution. More structures could be classified as standard in this period and were proven with a **safety margin** by using *design codes* and *calculation methods*.

Within the digitalisation age, *computation* and *automation* began to produce new forms of innovation, which slowly influenced the construction sector where conventional building methods were (and still are) very rooted. With *digital fabrication* and *new materiality*, structural innovation is rising again above the available safety methods, creating new non-standard building systems. This **research challenge** constitutes the motivation of this dissertation, which by learning from history and utilising the full potential of advanced structural methods, presents a methodology for the **integrated structural design of non-standard building**

Figure 5.2

Integrative structural design methods for the different types of non-standard building systems.



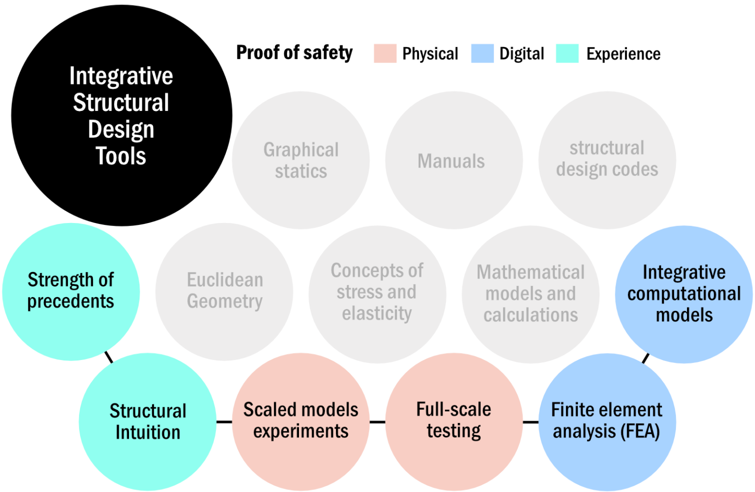


Figure 5.3

Proof of safety strategies proposed by the integrative structural design methods for non-standard building systems.

systems that can shorten the gap between what we envision to build and what we consider safe to build.

The design methodology presented should be used with *flexibility* and *adapted* to the needs of each non-standard building system. Figure 5.2 illustrates how the different non-standard areas can require different methods: **digital workflow**, **structural characterisation**, and **prototyping and testing**. The project requirements will influence the *number of design loops* needed or the *level of integration* with other disciplines.

As the structural design goal in any non-standard building system will still be the *design*, *optimisation*, and ultimately the *proof of the system's safety*, the workflow presented in Figure 4.1 can be considered as a complete set of methods and strategies for an integrative structural design scheme. Nonetheless, the steps and iterations to be applied for a specific structure would still need to be reconsidered or adapted to its design and structural requirements.

The strategies proposed to prove the safety of novel non-standard building systems do not differ from those used during history (Figure 5.3). On the contrary, the proposed methodologies overlap with those already used by great engineers who helped develop the non-standard systems of the industrialisation age. A great lesson from history is that experience, and physical methods can support the design when the *level of unknowns* is greater. Utilising the full potential of **digital engineering techniques** with **experience** and **physical methods** can be the key to overcoming the current engineering challenge.

In conclusion, it was demonstrated that the workflow needs to include **multidisciplinary** collaboration, emphasising the importance of **data integration** techniques. The design should be performed in an **iterative** way with fabrication and structural feedback, resulting in a **digital-phys-**

ical approach. The material **optimisation** is first completed when the aesthetic and performance objectives are satisfied by using the feedback loop between design and FEA assisted by physical scaled models.

The FE **modelling** should be flexible and adapted to a **multi-scale** and **multi-level** scheme, including models that run in parallel with different definition levels to identify misleading results. These structural simulations are informed by small-scale characterisation testing to set initial assumptions and are later **calibrated** through full-scale **destructive testing** during the optimisation and verification stage. The full-scale testing is designed to represent the worst-case loading scenario that produces maximum internal forces.

Finally, **safety** and **reliability** are reached by comparing the test results with the calibrated FEM. Including full-scale prototyping and testing in the design makes further **optimisation** to adjust fabrication and structural parameters also possible. Additional **quality evaluation** methods can be implemented during the process to reduce the number of full-scale testing, building confidence in the design and structural performance.

Advancing towards an *integrative design approach* that can be generalised for any non-standard building system, a more extensive evaluation of parameters should be made to be integrated into the *multidisciplinary computational design framework*, following the work already initiated in publication **P6**. Besides, if the ultimate goal of these structures is to produce more *sustainable architecture*, the evaluation of the structural system against other relevant factors, such as *live cycle assessment* indexes, could be implemented as a variable in the early design stages. The structural system sustainability aspect was briefly explored in publications **P9** with the evaluation of several alternative fibre materials suitable to the fabrication technique of CFW, and in **P5**, where the design was adapted following the requirements of the implemented natural fibre material system.

To sum up, the *integrative structural design* shown through its application in coreless filament-wound structures revealed the methodology's potential to prove **safety** and **reliability** of other non-standard building systems, shortening the gap between research and industry and facilitating the increment of *built innovative structures*. Future research should extend the methods to identify the adaptations needed for the validation of other non-standard building systems.

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