Textile steel - experimental investigations of textile fabrication processes for steel shell and lattice structures

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Abstract

Global steel production amounts to around 2 billion tons per year [1]. Half of the world's annual production of steel is used in the construction of buildings and infrastructure [2]. Steel is a material that can be recycled without loss of properties, a huge potential for urban mining and the circular economy, yet, the demand for new steel is higher than the offer of secondary raw material. Lightweight structures are saving material and can therefore help to reduce the extraction of materials through the primary route and optimise the use of secondary raw material, which can be extracted through urban mining [3].At the intersection of research and teaching, the paper examines the formation of concepts, starting from an understanding of materials and fabrication technologies and going forward to questioning and rethinking existing methods with strong focuses on computational design and digital fabrication processes that enable novel concepts for circular economy in construction. By applying fabrication concepts from textile technology, a series of steel structures were re-conceptualized, redesigned and prototyped. The material distribution was locally tailored, based on the interplay between geometry and structural behaviour. Several prototypes were built to validate the overall approach, and in a next step, recycled secondary building materials could be used.

Keywords: optimization, digital fabrication, form finding, steel, textile, metal, membrane structures, weaving, structural membrane

1. Introduction

Steel is a material that can be recycled without loss of properties, a huge potential for urban mining and the circular economy. Yet, the demand for new steel is higher than the offer of secondary raw material. The construction industry accounts for 50% of global steel production and consumes more than 3 billion tonnes of raw materials [3]. Steel is therefore a perfect case study for the implementation of circular material cycles in construction. Based on the principles of the technical cycle as described in the concept of circular economy by the Ellen MacArthur Foundation, the aim should be to avoid the extraction of materials through the primary route and focus instead on the use of secondary raw material, which can be extracted through urban mining. However, the recycled products must use the material more efficiently: recycling a conventional steel component into a multitude of components with locally tailored material distribution, while delivering the same function and strength as those created by traditional methods, could enable the industry to meet growing global demand. While steel is traditionally thought of as a heavy and rigid material, the availability of thin sections, wires and yarns allows a level of flexibility and adaptability which bigger profiles do not offer. The use of these materials enables it to be processed in a textile way, but still allows for the combination with established steel working processes such as cutting and welding. In this scenario, digital design and fabrication processes could enable the shift from the serial production of identical parts to the custom production of material-optimised components.

At the intersection of research and teaching, the combination of fabrication concepts from textile technology and concepts of resource-efficient steel components were investigated. Experimental prototypes made of steel wire and yarn, focusing on hands-on explorations and concept models were created.

2. Research and teaching method

The course explored a variety of concepts through a design-through-making approach. Starting from an understanding of materiality and existing technology, students then developed initial concepts through exploratory prototypes and realised three final proof of concept models through full-scale prototyping. Guided through three development phases, the course investigated processes, techniques and material properties in an initial phase to provide students with the technical foundations for the seminar. The second phase entailed the development of exploratory small scale prototypes to iteratively refine a novel digital design and fabrication concept for material-efficient steel components. The third phase of the seminar focused on validation of the developed concepts through physical prototypes on a 1:1 scale, while showcasing its architectural implications.

3. Phase 01 - initial investigations

Students investigated a varied range of textile processes and digital fabrication techniques, in search for manufacturing and processing techniques that enable resource-efficient, functional arrangements, utilizing material properties and mechanical techniques for steel. This created a reliable repertoire of knowledge on which the following development phases could base upon. This phase was complemented by skill-building tutorials for digital design tools to aid the concept specific design tool development. In all examined textile fabrication techniques variations in weaving, braiding or knitting patterns can be used to create 3-dimensional spatial structures.

3.1 Textile steel fabrication techniques

Weaving is the process of interlacing two sets of thread, yarn or sometimes other materials to create textile sheets. There are different variations of weaving techniques, but the basic principle is the same: There are threads that are pre-tensioned parallel to each other, the "wefts", and threads that run orthogonally to them, the "warps". By passing the warp threads, which are contained by the "loom", alternately over and under the weft threads, a textile can be created. Special warp knitting machines can produce "spacer fabrics" that create connections between two or more layers of flat fabric, or even create a honeycomb structure in cross section (as implemented by the Belgian company "3D Weaving"). Braiding is the process of intertwining three or more strands of flexible material in a specific pattern to form a three dimensional structure. Unlike weaving, braiding in its purest form requires no equipment other than the material itself, on an industrial scale automated braiding machines are widely established (e.g. braiding machines by HERZOG GmbH) [4]. Knitting is the process of making interlocking loops of yarn or thread using two or more knitting needles. The loops are created by pulling a loop of yarn through an existing loop, then pulling a new loop through the previous loop, and so on, creating a series of interlocking loops. On an industrial scale there are two main types of knitting: flat bed and circular knitting. By varying the knitting pattern locally, the textile can be brought into a three dimensional shape later (as implemented by Zaha Hadid Architects and ETH Zurich) [5].

3.2 Steel joining techniques

During the seminar, the students have explored various fastening techniques with a focus on interlocking techniques that do not require fasteners and are suitable for thin sections rather than sheet material.

Therefore, techniques such as riveting, nailing and screwing were not considered. Instead methods that do not need any additional heat or adhesives such as clinching and interlocking, as well as methods that uses heat like welding, brazing and soldering, were explored. For the development of digital fabrication concepts it was important to focus on steel joining methods which can be implemented using industrial robots. This allows complex 3d structures to be produced with millimetre precision. As such, traditional methods like welding and bending can be used and incorporated in form of robotic WAAM(Wire Arc Additive Manufacturing) or robotic wire bending [6][7][8].

3.3 Material behaviour

Keeping the different properties of steel in mind, several options had been considered. Each has different characteristics to suit specific applications. In most cases, iron is either combined with other materials such as carbon, chromium and nickel to form an alloy, or coated with zinc or oxidised to form a protective layer against corrosion. Typically, the dead weight of the structure is a small fraction of the applied load or generated forces. Lightweight structures often use light and high strength materials as well as advanced technologies for their design and construction. Many shapes are pre-stressed, resulting in double-curved shapes that require special cutting patterns and care during erection. Typical lightweight structures include cable, membrane, shell and folded structures as well as space grids, braced vaults and domes, arched, stayed and trussed systems. For the purpose of the seminar such structural principles and typologies were investigated regarding their potential as textile steel structures and building components.

4. Phase 02 - development of initial concepts

Exploratory prototypes were manufactured as small experiments to gain insights into materials, systems and structures as well as test key assumptions, strengths and weaknesses of the concepts. Produced in rapid iteration, this helped to formulate further research questions and address them in the next evolution, but also narrowed the investigations through research-based decision making.

4.1 Knitted steel

Aiming to produce building elements utilising steel and knitting techniques, required the conceptualization of a process starting with form finding, extraction of 2d knitting information which has the three dimensional shape inscribed, a forming phase in which the knitted structure is tensioned and a solidification step in which the tensile structure assumes bending stiff properties. Different options for the solidification of the structure were explored. Using the custom knitted steel membrane as integrated concrete rebar and formwork provides a stiffening effect that allows the structure to resist bending forces as commonly used in construction. Through experimentation, it was determined that spaced layers of fabric were beneficial to build thickness on the structure, allowing concrete poured onto the mesh to adhere more effectively. Another method of transforming a tensile network into a bending stiff shell structure is to use local spot welding or brazing to join the steel wires together at specific points or along the entire curve network length to create a stiff structure. Such a knitted steel membrane could therefore be conceptualized as a precursor for a subsequent robotic WAAM process. To fabricate the building elements, a form-giving strategy was devised, and an external frame was employed to put the knitted meshes of steel under tension, enabling tension-based doubly curved membrane geometries to be created(Fig.1).

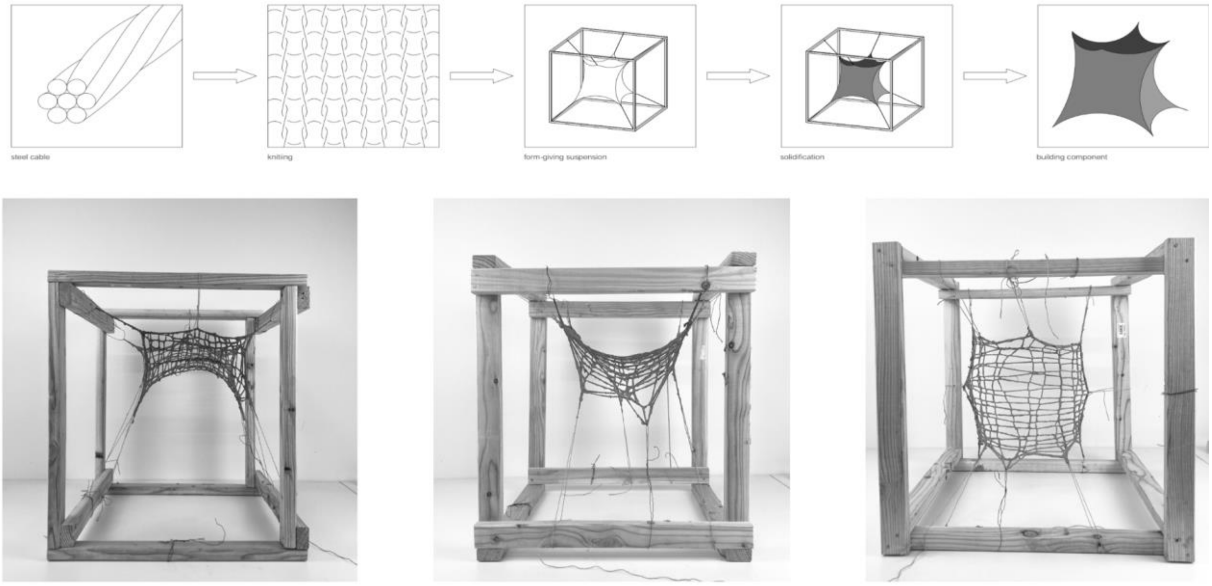

Figure 1. Production concept of steel knitting and first prototypes [Graphics and photo by authors].

4.2 Woven wall

The envisioned spatial weaving concept allows for a three dimensional interconnected network of steel cables to be spanned between a set of initial steel pipes. For building elements like floor slabs or wall segments, several hexagon patterns were subsequently merged into each other. These could either be lined up in a flat manner to develop slab like ceiling or wall components, or be spatially arranged into more complex geometrical configurations. The basic wire layout could be reinforced by subsequent locally differentiated reinforcement layers to provide differentiated structural capacity. Sleeves around the threaded rods separate the levels from each other and reduce the density of the structure as well as reduce the buckling length of the threaded rod. Vertical braces are woven in to provide additional stability (Fig.2).

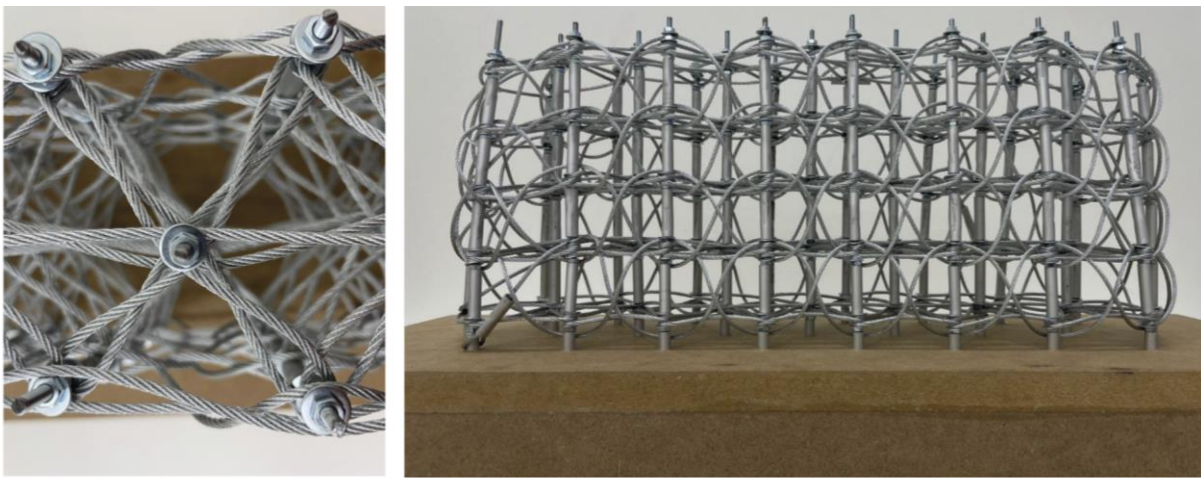

Figure 2. First prototype of steelweaving [Photos by authors].

4.3 Braided column

This fabrication concept utilises threaded rods which are intertwined by steel wire or cables through a braiding process. The steel cable is wound around rods to form connecting points, forming very fine mini-members of a spatial truss which is bracing the main parallel aligned members. The diagonally connected inner webbing supports the column and reduces the buckling length. Through the centre of the structure more cables tie the individual rods together to cope with the pressure forces resulting from vertical loads. These continuous wires represent the stiffening of the structure. The intertwined rods and wires are subsequently soldered and could conceptually be robotically spot welded to form load transferring nodes (Fig.3). Although locally consisting of weak members and connections the high resolution and redundancy of the structure could form a robust load bearing component.

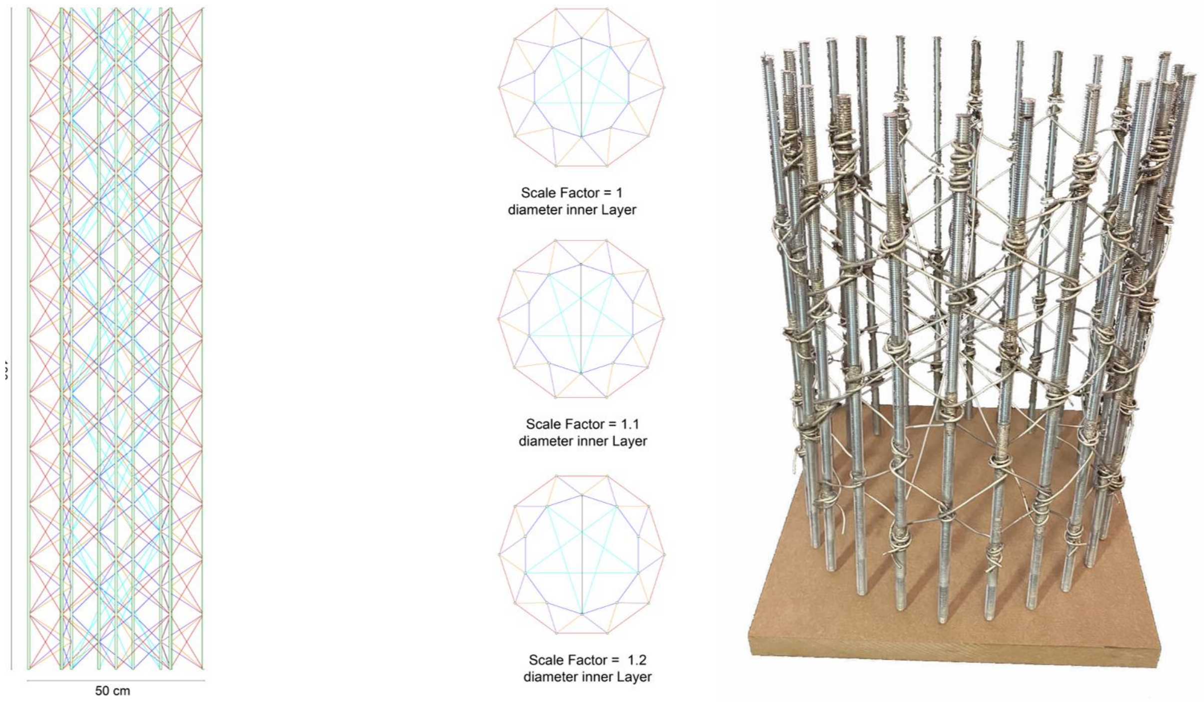

Figure 3. Production concept of steel braiding and first prototype [Graphics and photo by authors].

4.4 Metal distance weaving

Distance weaving is a fairly novel concept which is able to form multiple interconnected layers of fabric at once. Metal screen weaving on the other hand is practised for many decades and well understood. The concept aims to alter the manufacturing process of metal screen weaving in such a way that a rigid metal distance weave can be produced on an industrial scale. In a first prototype weaving pattern, the weaving process itself as well as the appropriate metal gauges were explored (Fig.4). The development of a process specific parametric design tool allowed to explore several different variations in thickness, patterns, as well as shapes of the structure. Through specific bending of the metal wefts of the 2nd prototype it was possible to prove the concept of inscribing curvature into the piece. This opened up the potential to inscribe information about the components global geometry into local machine bending instructions. Being able to form curved shapes opens up a wide range of possibilities from thin free standing walls to quick industrial production of mesh moulds for construction. Through the inscription of local deviation of material distribution, it is possible to tailor the structure to the specific application and load while using as little material as possible.

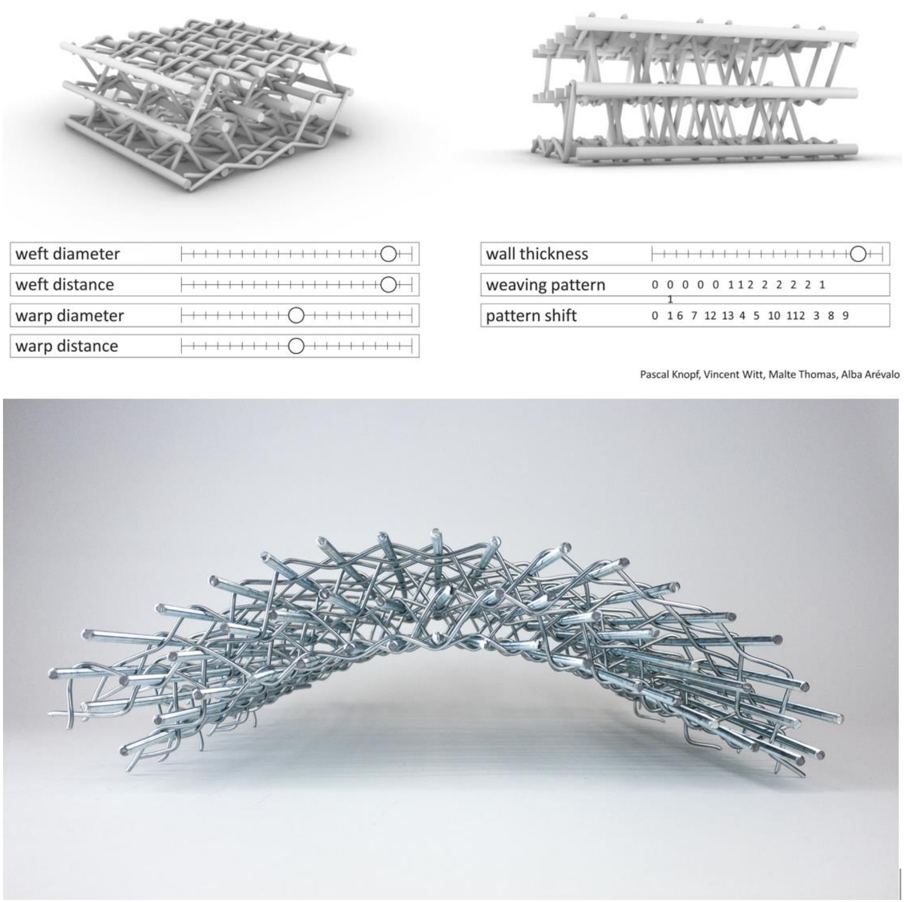

Figure 4. Production concept of steel distance weaving and first prototype [Graphics and photo by authors].

5. Phase 03 -1:1 scale explorative prototyping

The research of the third phase was driven by the bottom-up concept developments of the second phase process focused explorations and aimed at their translation into material-efficient building components based on simple structural models. Within the limited scope of a selected building element (e.g. column, façade panel etc.), each group carried out early qualitative design explorations for loading conditions to inform the material layout in high resolution and cross reference them for potential differentiation with the textile techniques investigated thus far. This resulted in three physical 1:1 scale, handcrafted prototypes, made of steel wire in varying gauges and yarn utilizing and scaling the techniques explored in the previous phases. Furthermore, the models were soldered, welded and galvanized(Fig.5) to provide structurally stable components. The final prototypes serve as a proof of concept at the intersection of research and teaching and validate the architectural potential.

Figure 5. Hot dip bath galvanisation of the final 1:1 prototypes [Photo by Daniel Fischer].

5.1 Braiding steel

Braiding techniques emerged as a concept from phase two to be explored further to interconnect paired rigid, straight, load-bearing braid strands with flexible strands to reduce the buckling distance of the load-bearing strands. The concept aims to explore an idea for lightweight, high-efficiency column structures using digital fabrication. The structure consists of vertical steel rods, which create its main skeleton; steel cables were braided between the rods to form the lattice structure. The diagonals, created by winding the cables around the rods, are digitally designed in continuous paths from the bottom to the top, an important aspect considering later potential for its implementation in a fully digitally controlled textile braiding process. The structural concept of the column has been extended through a double layered rod structure with local buckling bracing and a second layer was introduced within the inner core where cables create a secondary web to further strengthen the column. The entire structure was galvanised by immersion in a zinc bath to fix the braided structure in place and to provide a layer of adhesion and slip resistance at the interface between the rigid rods and the flexible steel cables. In a next step, the concept could be adapted to slab applications such as roof trusses or ceiling structures by modifying the manufacturing setup, which is currently conceptualized for circular linear construction members.

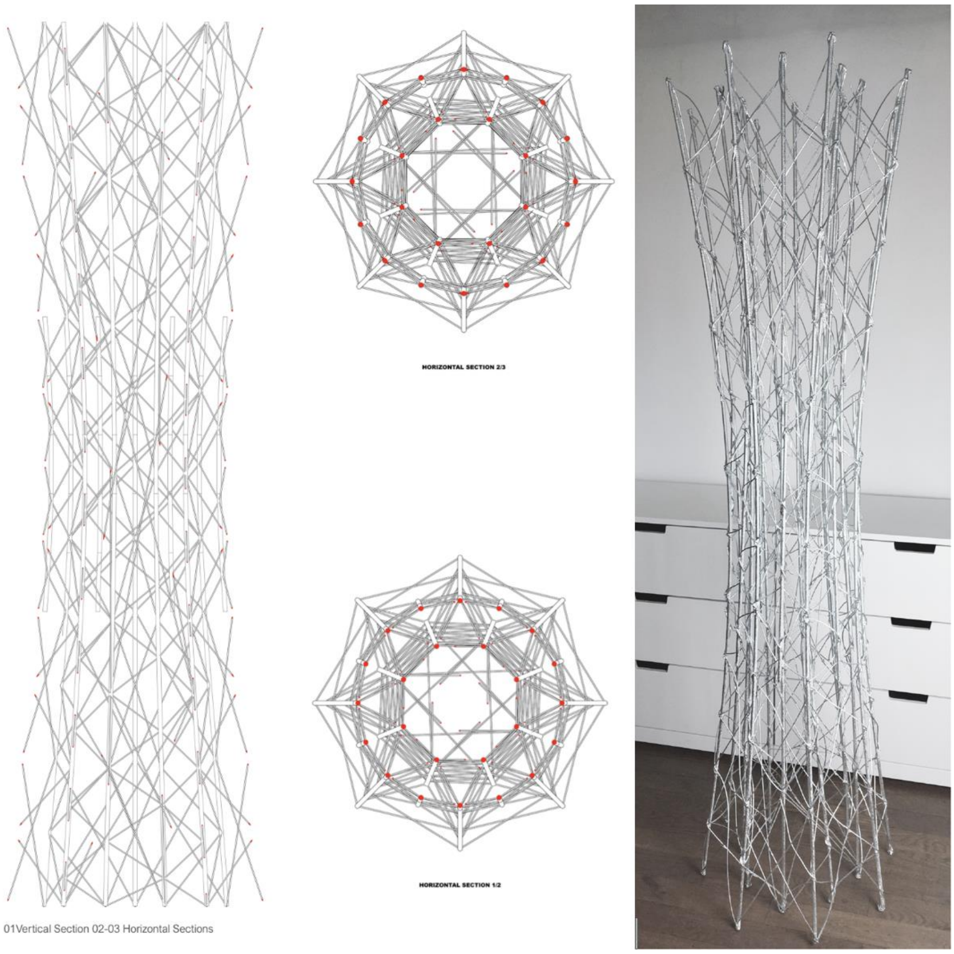

Figure 6. Production concept of steel braiding and second prototype [Graphics and photo by authors].

5.2 Weaving steel

The second 1:1 prototype resulting from phase three continued the exploration of industrial weaving techniques and applied them to steel components to create structures that are based on mechanical interlocking, thus enabling the structure to be fully dismantled after use and creating a closed material cycle. The process is derived from the looms used in the industrial manufacturing of woven textiles (Fig.7).

By adjusting parameters of the structure through the parametric design tool according to the differentiated requirements, such as structural load, the desired shape was found. The adaptable parameters are: weft and warp diameter, distance between wefts and warps, bending patterns as well as bending pattern shift. These parameters are derived from the global design of the geometry. Conversely, the specific sequence of wire bending instructions to the machine inscribes the global geometry and especially curvature into the produced part. Through varying these parameters, a high degree of local differentiation of the resulting properties of the structure is achieved resulting in a variety of possible geometries (Fig.2). The wefts and warps only form a connection through mechanical interlocking, thus enabling the structure to be reused or remanufactured. Other than as rebar the structure can serve as installation walls, facade elements, partitioning walls as well as plant racks or lattices. The manufacturing technique that was developed for the concept could become an industrial alternative for rebar installation, which usually requires great amounts of manual labour.

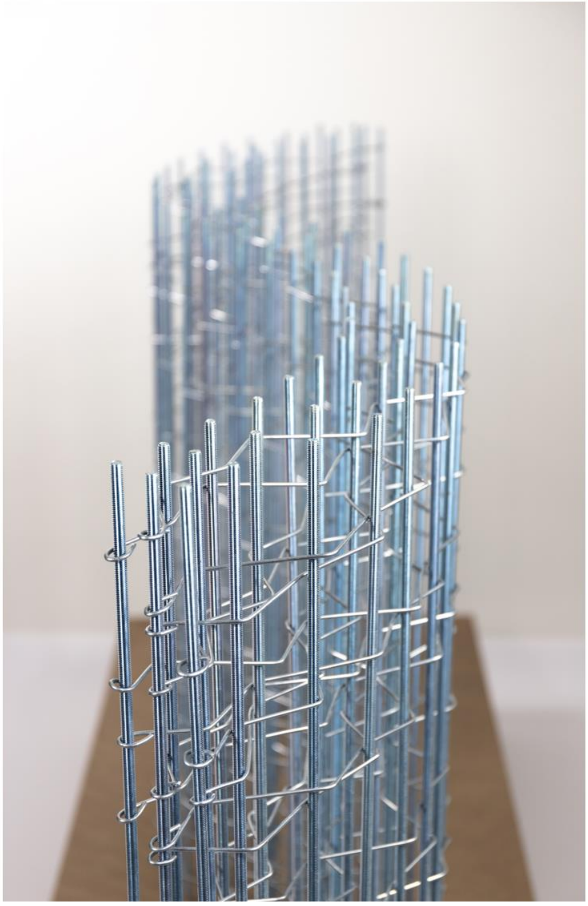

Figure 7. Final 1:1 prototype of weaved steel wall [Photo by the authors].

5.3 Knitting steel

The third 1:1 prototype resulting from phase three built on knitting techniques in combination with thin steel cables to create facade elements that are locally differentiated for shading and aesthetics, as well as material distribution. The concept is based on knitting a 2D mesh and using an external framework to suspend it. In this way, it is possible to navigate the textile repertoire of form found membranes as doubly curved lightweight structures. The form found membrane geometry enables the forming process during fabrication and provides structural performance as shell action in its final bending stiff configuration.

Different knitting technique patterns were investigated through the initial exploratory prototypes. By reducing the knitting patterns to three basic principles it was possible to create a pattern that offers great variation in terms of density and resolution but also enables ease of production. Different options for the solidification of the structure were explored in phase two. The 1:1 mock up realized in phase three utilized zinc dip bath galvanization to locally stiffen and bind the steel cables together. As an outlook this process could be replaced with a robotic WAAM process to locally thicken and stiffen the spatial metal network.

Digital tools were utilised as form-finding workflow for the concept. In particular, a physics simulation was used to adapt the behaviour and the final shape of the membrane according to potential positions of integrated building component connection details and tailored density of the knit. This also allowed to gain an understanding of the required fabrication bed size for potential future automated flat knit fabrication and varied density distribution to form the membrane.

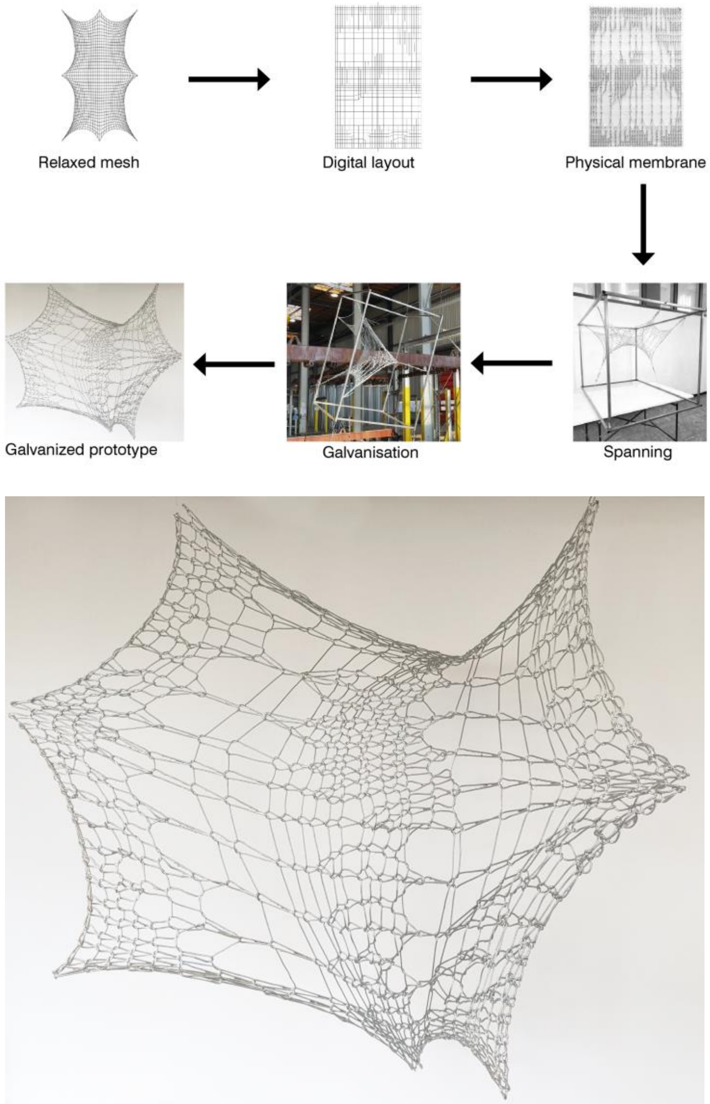

Figure 8. Production process of steel knitting and final prototype [Graphics and Photo by the authors].

5. Conclusion and outlook

We were able to show that through digital design workflows, a critical review of textile manufacturing techniques as well as a gained understanding of the interplay of steel and textile processes it is possible to generate new concepts for building technologies out of steel which offer the ability of local differentiation while reducing the amount of material used. Two of the three explored concepts make use of zinc galvanisation to stiffen the structure, through this process the recyclability of the resulting structures is impaired. Further development of the concepts should include processes to replace the zinc galvanization in order to keep the products mono-material structures. The seminar project revealed several design and fabrication related research questions as starting points for future research endeavours into digital circular construction concepts for steel structures.

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