buildings

Article

Introducing Concrete Fabrication into Ferrocement: A Study on the Shape-Making of Cement Mixture

Fei Chen [1,*], Sibo Pang [2] and Wanhong Yu [2]

[1] School of Architecture, The Chinese University of Hong Kong, Shatin, Hong Kong 999077, China
[2] Bartlett School of Architecture, University College London, London WC1E 6BT, UK
* Correspondence: feichendesign@gmail.com

Abstract: Widely used in the making of sculptures and prefabricated building components, ferrocement is considered to be beneficial to environmental preservation. However, there is still little attention paid to the making shape and design of the ferrocement in the literature. Moreover, there are some disadvantages associated with ferrocement, such as the lengthy and complex process of binding poles and nets together. The research question to solve in this paper is about how to study the making shape of ferrocement when solving these disadvantages, so as to improve the characteristics of ferrocement. In this research, a dialogue is conducted between concrete fabrication and ferrocement, the focus of which is placed more on the material and craft instead of robotics as the recent frontier of concrete fabrication. By replacing the standard wire mesh in the ferrocement with steel, how to make the steel plate from two dimensions to three dimensions, and then assemble them into a steel skeleton is explored. Then, the craft of casting is studied for integration of the cement mixture into the steel skeleton and its tight attachment onto the steel surface with spraying. Apart from that, a digital software is applied to the simulation and design accompanied by physical experimentation. To sum up, the research demonstrates the potential of free-forming of the ferrocement and its application in the (prefabricated) building technology, with questions raised for future study.

Keywords: ferrocement; shape-making; concrete fabrication; 2-D to 3-D; spraying the cement; digital simulation; prefabricated building technology

Citation: Chen, F.; Pang, S.; Yu, W. Introducing Concrete Fabrication into Ferrocement: A Study on the Shape-Making of Cement Mixture. *Buildings* **2023**, *13*, 256. https://doi.org/10.3390/buildings13010256

Academic Editor: Elena Ferretti

Received: 10 November 2022
Revised: 22 December 2022
Accepted: 5 January 2023
Published: 16 January 2023

1. Introduction

Ferrocement is defined as "a composite construction material that consists of closely spaced single or multiple layers of steel mesh with or without skeletal steel support". In some cases, it refers to the thin-shell concrete [1]. As a mortar or gypsum pouring technology intended for the metal layer, ferrocement construction technology, also known as thin shell concrete, is applicable to produce ships, building shells, roofs, and water tanks with thin or strong forms. It is widely adopted for making sculptures and prefabricated building components. Extended to some non-cement materials, the concept of ferrocement has been commonly practiced due to advantages such as low material cost, flame retardancy, and the ease of shaping, etc. Ferrocement is regarded as a sort of "green material" [2] because it can be made of local resources, beneficial to environmental preservation (ferrocement structural elements have long service life) and can be repaired with low consumption [3]. Therefore, it is worthwhile to study and improve the craft of ferrocement.

Up to now, ferrocement has been widely studied. On the Web of Science (WoS), there are 485 papers themed with "ferrocement". Despite this, there remains a lack of research on its shape-making, especially the free-shaping of ferrocement. Ferrocement is disadvantageous in some aspects, such as the lengthy and complex process of binding poles and nets together, and the corrosion of reinforcement materials due to the incomplete coverage of metal by mortar [4]. Considering this, the research question in this paper is how to study shape-making when these disadvantages are solved, to improve the characters of ferrocement. This paper establishes a dialogue between concrete fabrication and the ferrocement to explore the potential of taking shape in the ferrocement.

As an integrative study of material, shape and craft, the research involves the following steps: the shape-making of steel plate (and how the units can be assembled into a furniture or a column), the craft of concrete, and the digital software used for design and analytical simulation. Instead of using the standard wire mesh in the ferrocement, the steel plate is laser-cut with water jet to make 3-D shapes. The three-dimensional components are assembled to create the skeleton of architectural space and then the cement mixture is added onto steel skeleton by spraying. The research aims to develop a creative method of shape-making for ferrocement with the assistance of various digital tools.

The present study starts with a literature review on ferrocement. In the introduction of this paper, the research gaps in relation to the ferrocement are indicated and addressed. The following session will elaborate on the research methodology, including the physical tools used to test the material and the digital software used to simulate this process. Next, the results of research and design will be presented. This session consists of these parts. The first one is to shape the single unit with such materials as paper, plastics, and steel plate. The second one is to assemble the units into a chair or a column. The last one is to show the casting results and perform the digital simulation. On this basis, the conclusion will be drawn and a discussion will be conducted about what can be learned from the research process, including the reference provided by the research results for real construction and the future focus of research.

2. Literature Review

2.1. Ferrocement and Its Disadvantages

At present, reinforced concrete (RC) has been extensively used in buildings and highway infrastructures. Around the world, the first known reinforced concrete was a ferrocement boat in 1847 [5] (p. 14). In early 1940s, Luigi Nervi redeveloped the concept of ferrocement when he "observed that reinforcing concrete with layers of wire mesh produced a material possessing the mechanical characteristics of an approximately homogenous material and capable of resisting high impact." [5] (p. 15) In this respect, the thin slabs of RC are highly flexible and strong. As argued by Kaish et al. (2018), the prior literature has focused much attention on the advantages of ferrocement over the FRP and steel, such as its cost competitiveness in the developing countries [6] and its higher in-plain shear strength than the Fiber Reinforced Polymer (FRP) sheets [7]. Meanwhile, however, ferrocement is also disadvantageous. In the past, it was used in thin shell structures, so its shape-making is limited. It is also a particularly complex and lengthy process to bind poles and nets together, and the corrosion of reinforcement materials may occur due to the incomplete coverage of metal by mortar without the tight fit between them [4]. In this research, these disadvantages will also be addressed when the research gaps of the ferrocement is emphasized.

2.2. Research Gap of Ferrocement-Taking Shape

The recent literature in relation to ferrocement focuses on behavior (76 times), performance (42 times), concrete (34 times), strength (32 times), reinforced concrete (18 times), repair (17 times), beam (16 times), and mechanical property (14 times) if the key words derived from the paper of "ferrocement" in the core collection of Web of Science are counted (Figure 1). The main subjects of highly cited papers on ferrocement include high-performance ferrocement laminate [8], the bolted shear joints in industrialized ferrocement construction [9], rehabilitation of corroded RC Columns [10], retrofitting shear-deficient RC members [11], most of which pay close attention to the structural and material properties of the ferrocement. However, there is lack of attention paid to discussing its "design" and "shaping", especially the free-shaping of ferrocement. Therefore, it is essential for the academics and practitioners to understand the potential of using ferrocement in architecture, especially in digital fabrication and the construction of streamlined architecture. Bending the rebar is a traditional way of shaping the reinforcement. However, it is not suitable for free-forming in the process of fabrication.

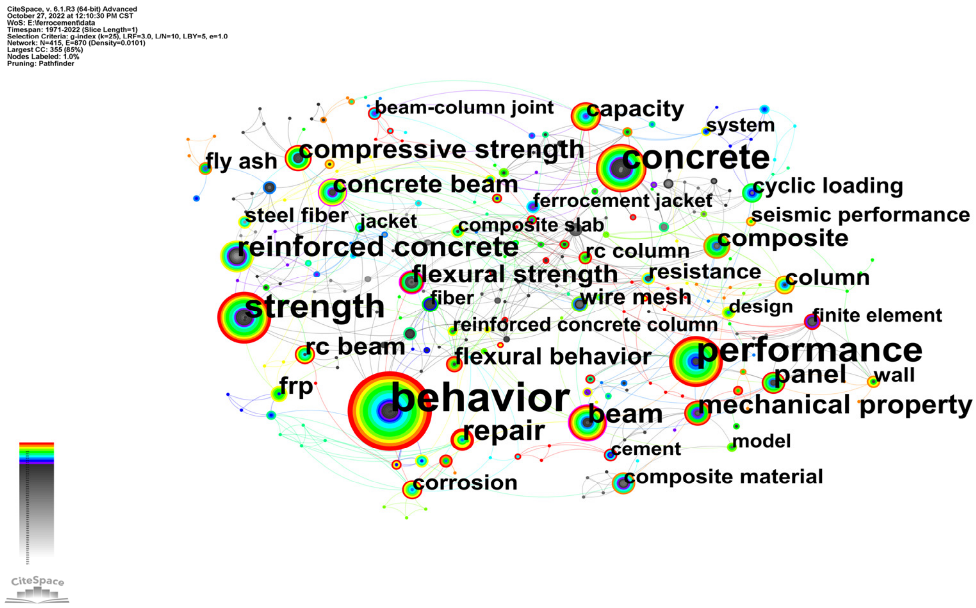


Figure 1. Co-occurrence graph of the keywords of the "ferrocement" literature, from Web of Science's core collection (data until Nov 2022).

2.3. *Setting Up Dialogues between Concrete Fabrication and Ferrocement*

Herein, the concept of "concrete fabrication" is introduced into ferrocement. Most of the recent research on concrete fabrication pays attention to integrating advanced digital technology (such as robotics and 3D printing) with the concrete design. Hamidi and Aslani (2019) reviewed the application of 3D printing technology in the cementitious materials and fabrication, highlighting its importance [12]. Nuh, Oval Orr and Shepherd (2022) obtained curved concrete shells via automated robotic concrete spraying [13]. However, other than the robotic technology, one core of fabrication "craft" is neglected in the literature. More attention should be given to developing the craft in concrete fabrication.

3. Research Methodology

The research is a systematical study of ferrocement's fabrication. The research methodologies include those of shape-making of the mold/skeleton, crafting and digital technology. There are several methodologies applied in different steps. The relationship between materials and shape-making is closely monitored, and the application of digital technology in it is discussed.

3.1. *Previous Methodology of Ferrocement*

Maharashtra Engineering Research Institute [14] (p. 2) defined the basic ferrocement methodology into three steps: "(1) Welding skeletal steel framework; (2) Tying mesh reinforcement tightly over its form cage; and (3) Impregnating the mesh cage with rich cement mortar, finishing and curing". Its common materials include "(1) skeletal steels in the form of angles, steel bars, weld wire fabrics or pipes; (2) steel wire meshes for forming cages, and (3) rich cement mortar, as matrix in form of micro-concrete" [14] (p. 7). In order to explore ferrocement's potential of shape-making, new methodologies and materials are explored.

3.2. *The Starting Materials*

Given the lengthy process of binding poles and nets together, there are a lot of different materials compared for uses as the concrete mold or the skeleton (Figure 2). An experiment is performed to test the cuboid (with the span of 225 mm and the height of 15 mm) made of different materials (Aramid fiber, polyethylene fiber, carbon fiber and steel net) in the gypsum (to simulate the concrete). The experimental result shows that the fiber is difficult to tighten, and steel net produces a much better effect of enhancement than the fiber that could not be tightened. Among them, steel is easy to bend and becomes stronger when it is bent. Therefore, steel is primarily chosen in this stage as the reinforced material for the ferrocement.

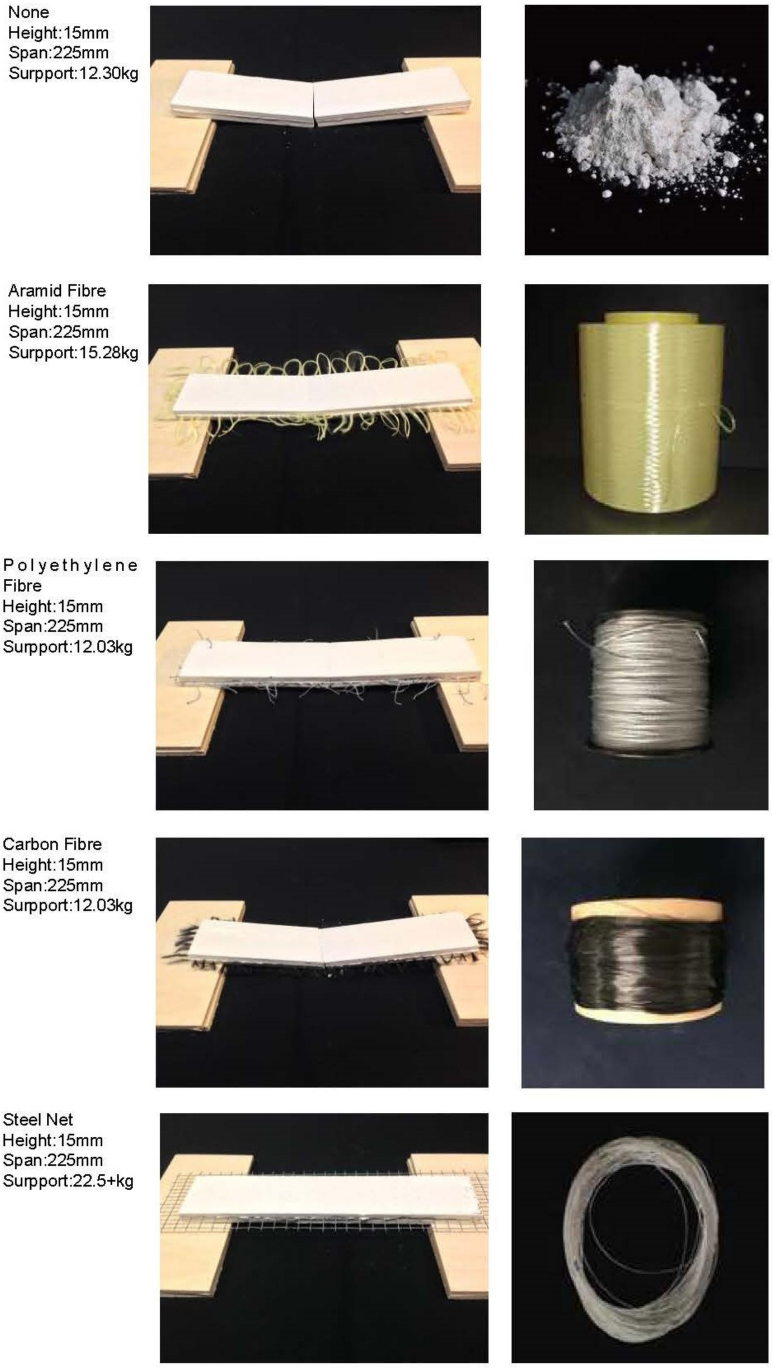


Figure 2. An experimentation gypsum mixture obtained when different reinforced materials (steel and fiber) are put into the gypsum cuboid.

3.3. The Making of Mold or Skeleton: Making Shape of the Steel

Steel fabrication (the steel sheet with 0.3 mm is chosen in the experimentation because it is easier to bend compared with thicknesses greater than this) requires bending, welding, water jet cutting and machining [15]. In this research, there are various patterns created out of the steel plate by cutting, such as holes and line. Moreover, what happens when the steel plate is stretched, bent or rolled is observed. In this step, the patterns are obtained on the steel plate through cutting by High-Pressure Water Jets.

Given the high cost of Water Jet's cutting, plastic and paper sheets are used before the cutting of steel plate to simulate the shape-making from two dimensions to three dimensions in the design process. In order to bend or fixate the three-dimensional paper in a standardized way, some wooden devices are designed with laser-cut and assembled craft to fix the corners of the (paper, plastic, or steel) three-dimensional skeleton. The rivet is used to assemble the components of 3-D steel skeleton if they are interconnected edge by edge [16]. The welding has not been used here because rivet is quicker, easier and looks better. Moreover, since most welding methods use part heating, the weldment after welding will inevitably produce certain welding deformation and welding stress in the structure, thus affecting the bearing capacity, processing accuracy and size stability of the structure. If the units cannot be made in contact with each other, small-sized joint sheet can be used to link them together.

3.4. Research on the Casting

After the design of steel skeleton, the casting process is experimented on. The traditional casting technology is to produce the mold and then the concrete is poured into it. Our common understanding of concrete casting methods includes the following steps: 1. Preparation, 2. Mixing the ingredients, 3. Placing the concrete, 4. Curing, 5. Releasing concrete, 6. Finishing [17], and a suitable mold is important to make the concrete take shape. However, it is difficult to make a mold for the skeleton in this experiment. Wiping the cement on the surface of the steel skeleton is tried but find difficult to realize, and its thickness is hard to control. Therefore, some alternative methods are tried and finally it is decided to spray the surface of the steel with the cement via shotcrete. The "Aflybltol" sprayed hopper tool (the famous spray manufacturing and craftmanship) is used as research tool of the casting research. Additional experiments are performed to trial different mix ratio between the cement, water and polyvinyl alcohol (PVA) because the cement may be hard to attach onto the surface of the steel sheet.

3.5. Digital Tools

Various digital software, such as Rhino, Grasshopper, Kangaroo and Karamba, are also applied to analyze the mechanical structure, simulate the shaping process, work out the design of the column and perform a further mechanical calculation for the structure. Regarding the simulation, the basic sequence of simulation is to find logic (shape finding), set the logic and action of a single module, find the combination mode between modules, select modules, and combine growth. Moreover, the simulation needs to find a tool that is close to the generation and evolution of physical form. Grasshopper itself is a deductive plug-in based on 3-D models. Its batteries also match the stretching, connecting and turning actions in reality to ensure consistency between simulation and reality. In the process of simulation, the possibility of multiple forms of the same model can be studied through the selection of different force application points and the setting of different stretching scales. The setting of different gap sizes, together with the force analysis of Karamba, can be used to determine the stress weak points of a single unit and the reasonable deformation scale of each unit. Through various forms of simulation, we can explore the potential of more forms under this generation's logic.

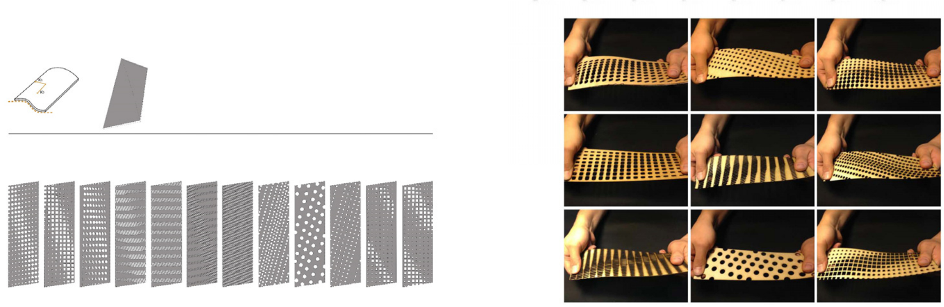
4. Research Result

4.1. Shape-Making of the Single Unit: Paper, Plastic, and Steel Plate

The project is part of the research project undertaken by the ferro lab team, the focus of which is on shape-making with different materials, especially the concrete. The project starts with an exploration into how the reinforced concrete can be made into a free form.

In real construction, the most widely used material of reinforcement is steel, especially poles and wire mesh. Furthermore, there are some cases where other sorts of materials are used as replacement. Bending the rebar is a traditional way to shape the reinforcement. However, its shaping is highly constrained by this method, especially for the free form. After different reinforcement materials are tested, steel is identified as relatively more capable of self-support with malleable consistency. Moreover, it is more easily bendable.

According to this observation, if patterns are created on the wood or steel plate by cutting, it would be easy to bend them (Figure 3). So, different patterns, such as the holes and lines, are experimented on with the wooden or steel plate (Figures 3 and 4). After the iron plate is cut, an attempt is made to pull it in all directions to form a spatial structural unit. This element is treated as the basis of the column geometry. However, the sheet can only be bent and the shape-making of it is quite limited with these patterns.



(**a**) (**b**)

Figure 3. (**a**,**b**) The holes of different forms and densities are tried on the wood because of the ease to use the laser cutting machine. Moreover, the methods of cutting on the metal are still not developed in this stage. The shapes shown on the sheets are starkly different from each other, including circle, square and the rectangle. Grasshopper is used to assist in creating the patterns. Through the experiments conducted on the wooden sheet, the research team draws a preliminary conclusion that to increase the density of holes or stitches makes it easier for the sheet to take shape.

Figure 4. After the simulation performed on the wooden sheet, the shaping experiment is carried out on the steel with a lot of holes. It consists of two layers because it is supposed to be a possible mound in the future study. At these stages, the members of the team dig out of the holes on the sheet steel manually. Therefore, it is quite difficult to control the shape and density of holes in an accurate way. This metal sheet is full of holes, which allows it to be bent effortlessly if bigger holes are formed by cutting. In this case, the problem is how to cut the metal in a way that is suitable for shaping.

Inspired by Chinese traditional paper-cut (拉花剪纸艺术), a method of shape-making is developed through repeated experiments on the relations between the shape of the sheet, the pattern on the sheet and the three-dimensional shape that can be created out of the sheet (Figure 5). With the different pattern and different lines, created on the paper/steel plate, it can be stretched to some specific shapes, as shown in the Chinese paper-cut in Figure 6.

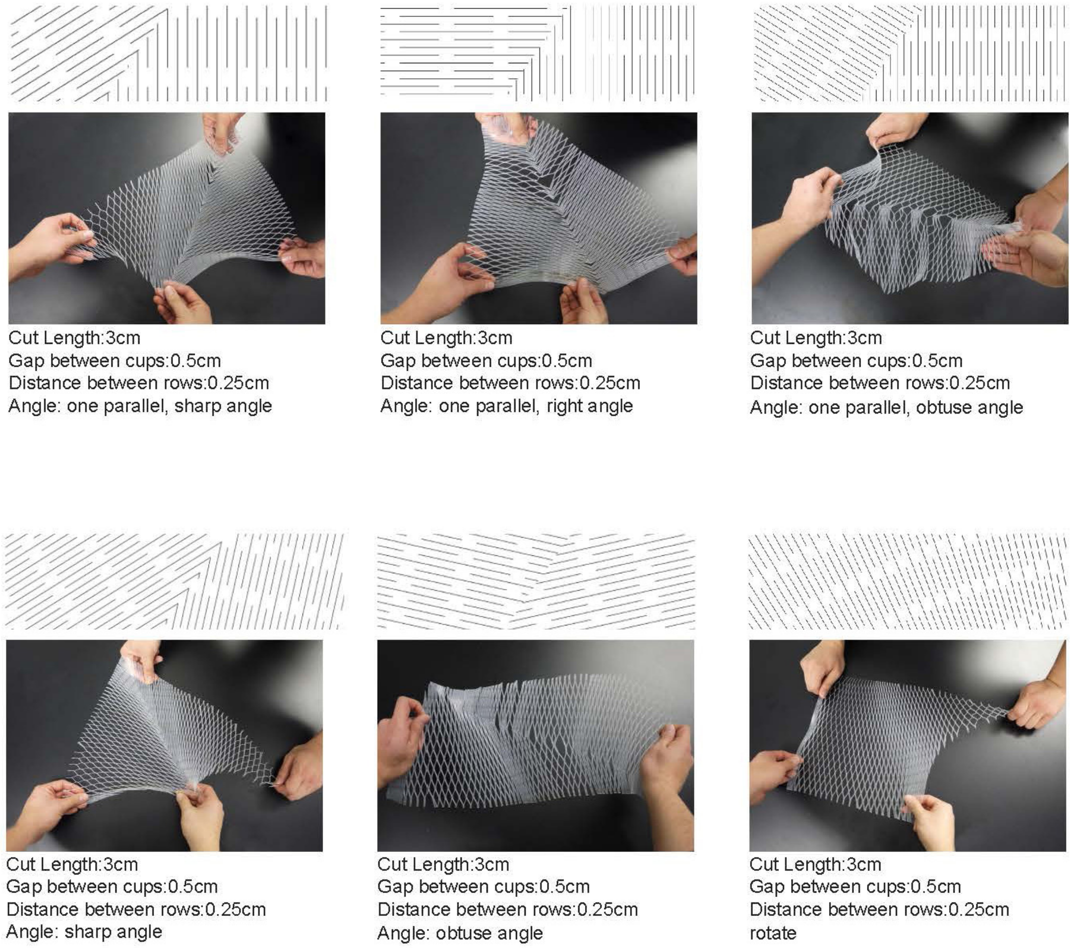
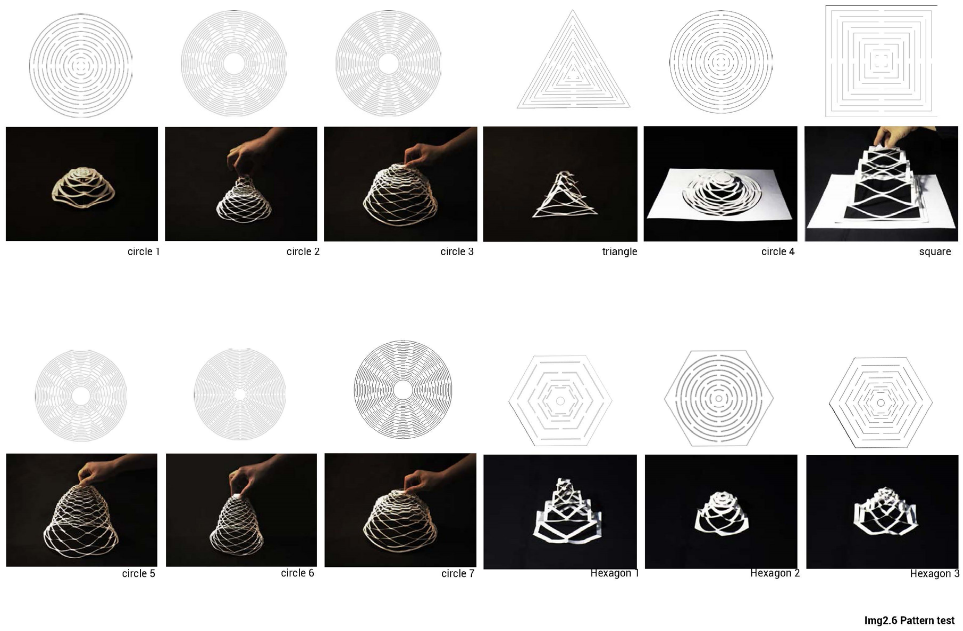
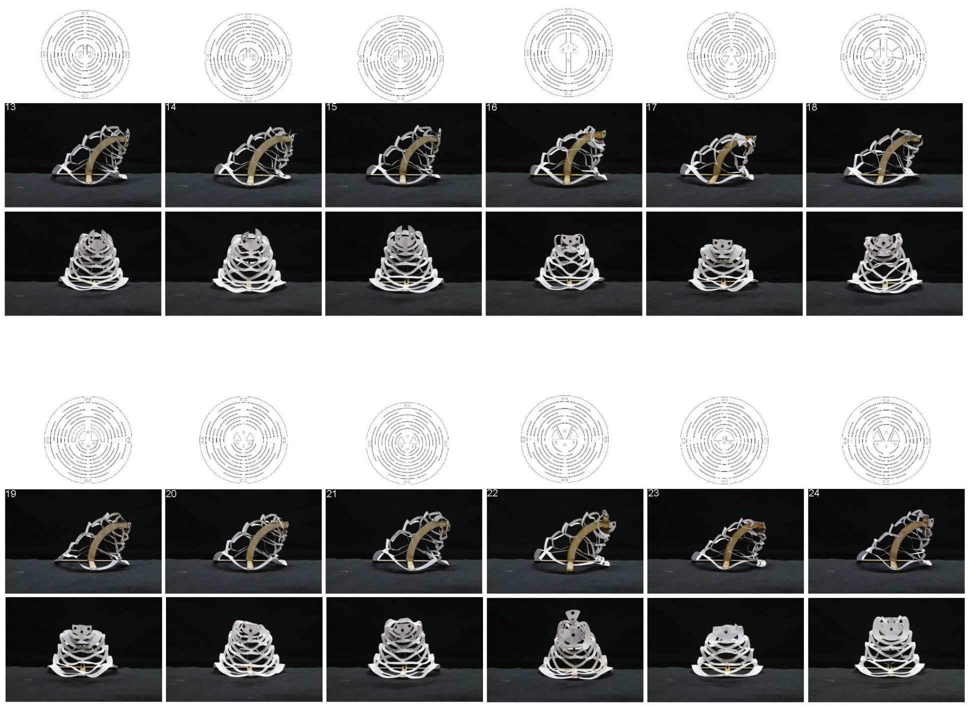


Figure 5. The relationship between the shape and the patterns, with plastics used for experimentation. Different patterns, with different angles with the same cut length, gap between the cups and distance between rows, are created by cutting out of the same plastic sheet.

The team makes an initial attempt to cut the pattern into a variety of singular planar shapes such as square triangle and especially circle. The circle is stretched upwards vertically or at a 45-degree angle. Used for pulling with a pattern with axial symmetry, the 45-degree unit encounters a problem, that is, some holes can be pulled to the extreme, but other holes can be barely pulled (Figure 7), although the experiment shows that bending significantly improves the strength of steel. Therefore, this pattern is unfit for bending. The team also tries to create the patterns by continuously cutting the same paper sheet (with multiple shapes). Then, the paper with serial circles is stretched into columns. However, the 3-D column is found to be difficult to bear force upon and it stands a big spring. After the trials with the combination of circles on a whole piece of paper, the team finds that the circles have many limitations. At first, the circle has insufficient ways of variation on shape-making and the structure made with circles is not strong enough; therefore, other pattern needs to be found with these methods. The team cuts some random patterns on the sheet steel with precise methods. Moreover, from this experiment, some conclusions were obtained. For example, if the single shape is small enough, it is hard to pull them. Moreover, the hexagon shape enjoys many advantages over the circles. There are several ways to make the shape as complex as possible for a single unit (single hexagon or multiple hexagons) chosen from the above experiments (Figures 8 and 9). Furthermore, the team cuts a series of patterns on one big single piece of sheet metal instead of assembling a series of similar units. In order to obtain a small column, there are many diamonds on one paper organized together to grow in the Y axis (Figure 10).



(**a**)



(**b**)

Figure 6. (**a**) Different single shapes as simulated with paper; (**b**) the experimentation: pulling the pattern at the angle of 45 degree, as simulated using paper. A series of trials are obtained to find out which pattern is easy to bend; the test aims mainly to find out the relationship between the shape, cutting length and bending length.

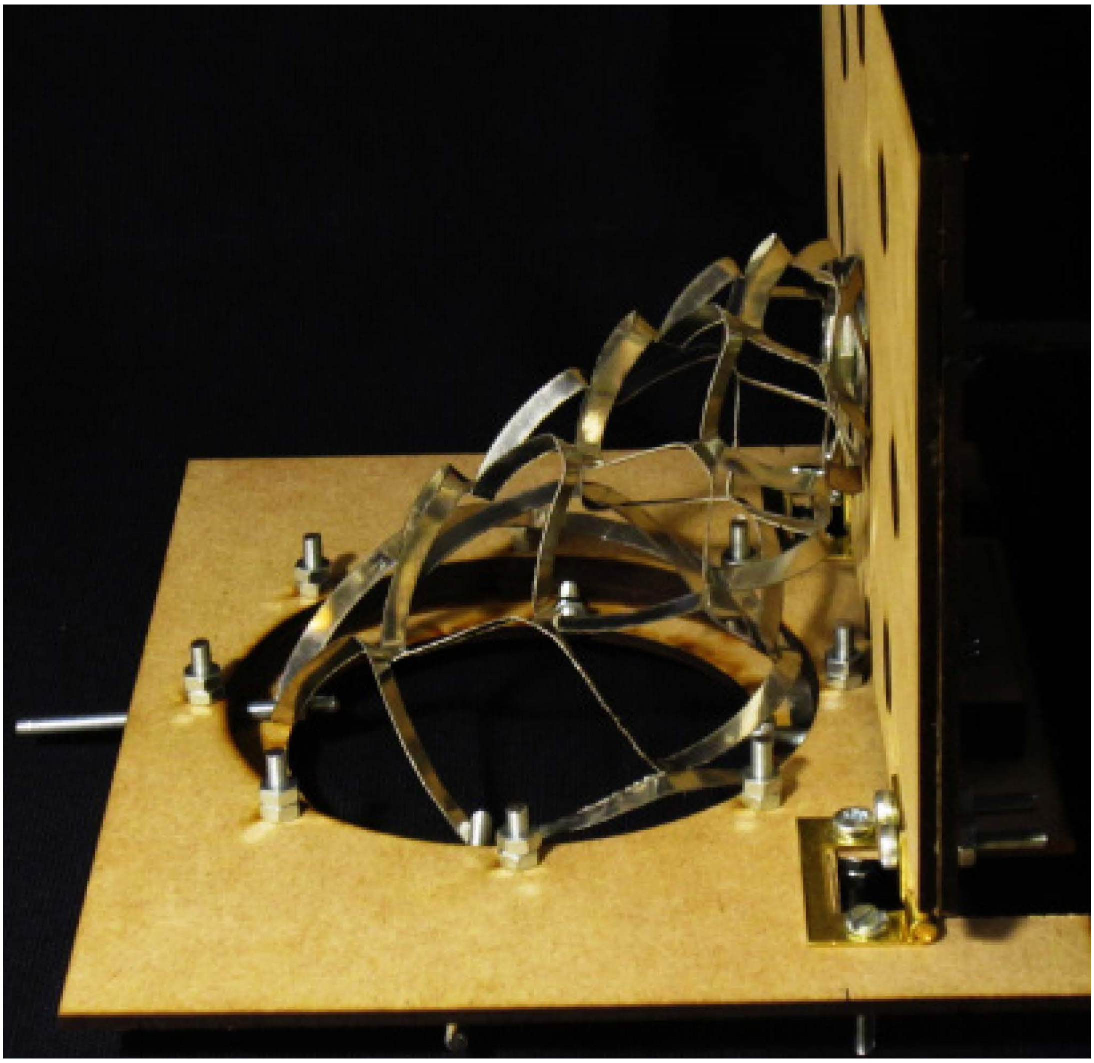


Figure 7. The equipment designed to pull the steel garland at the angle of 45 degrees. The device is designed similarly to a book, which allows the steel sheet to be pulled as accurately as possible.

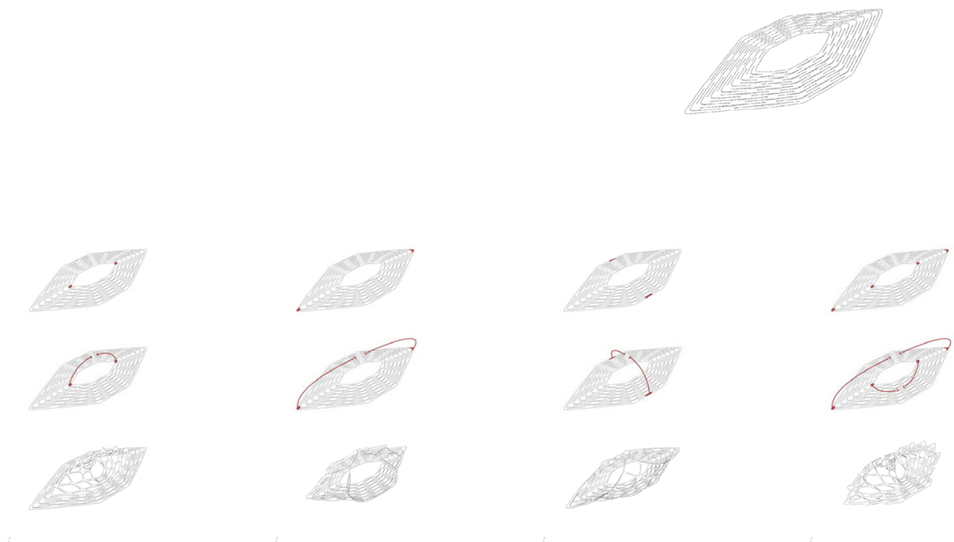


Figure 8. The pulling of the single hexagon shape on the steel plate.

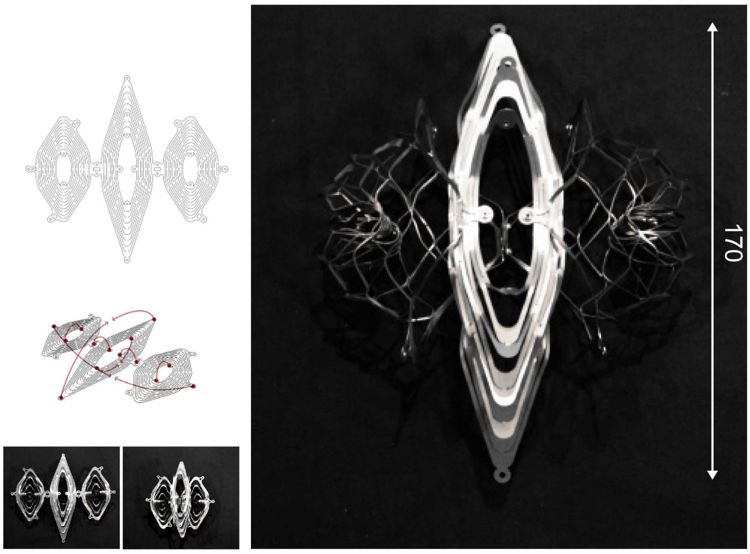


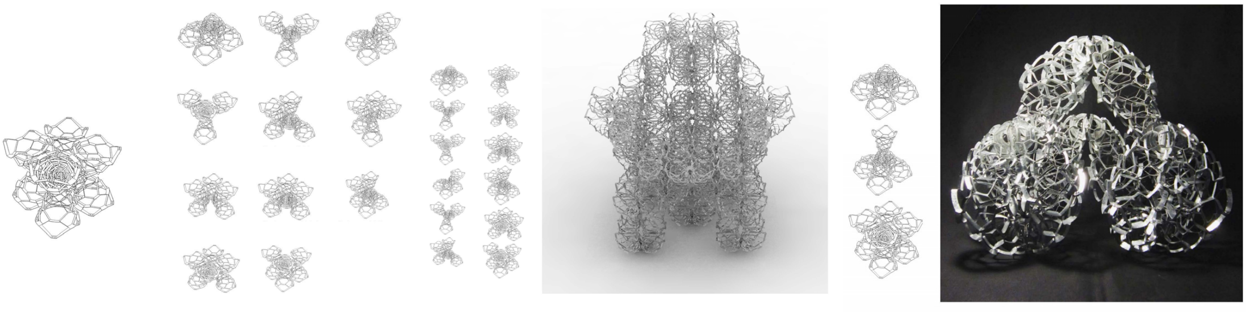
Figure 9. The unit made of three hexagons. Three hexagons are combined and pulled in two different directions, for comparison with the shapes obtained by pulling from one direction before. The advantage of this method is that the shape is strong. This is a prototyping unit to be developed as a column.

Figure 10. Different columns/units which are made of one piece of paper (for the simulation). There are multiple hexagons on one paper. The lines are drawn on the paper via laser cutting.

4.2. Assembling the Units

Based on the different patterns and different direction units, the connection between them in order to make a group is to open up more possibilities of (same) unit combination. One bending component cannot easily keep its shape, and if two bending components are designed to connect, the whole shape can be generated by itself. This kind of self-shaping way allows the shape to be more stable. The group can be assembled to constitute a large-scale skeleton. It has the potential to evolve into an architectural element (Figure 11). The units of serial circle are made into the shape of a chair and rivet connection is used here to connect the units while improving the strength of the whole structure (Figure 12). Therefore, it can withstand a higher pressure. However, its shape making is highly limited.

In the next step, the hexagon shapes are integrated into columns. The photograph shows the folded paper model as one of the prototypes produced for the steel skeleton of two steel sheets (Figure 13). Then, a model is made from several piece of paper with multiple hexagons folded and rolled in a particular order, into a column of around 2 m (Figure 14). The whole steel column takes 3 days to complete for the research team.



(**a**) (**b**) (**c**)

Figure 11. Different means of assembling the same units (in the circle shape): (**a**) the diagram on the left shows a column comprised of eight units; (**b**) the diagram in the middle shows a chair composed of these units via simulation in the Rhino; (**c**) the picture on the right shows one possible steel structure which was assembled by the circular units.

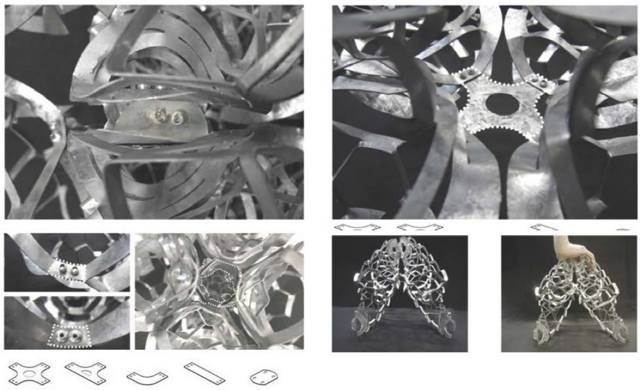


Figure 12. The rivet is used on the joint point of the steel skeleton to strengthen its structure.

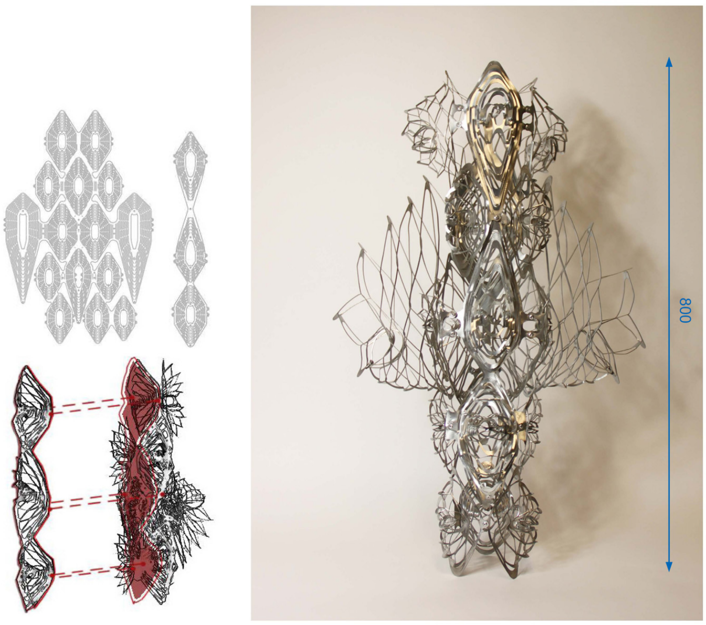


Figure 13. A steel column as assembled by two steel sheets. These two steel plates are of multiple hexagon shapes on them and connected by the rivet. The column continues to develop five rows of hexagons, pulled from positive and negative directions, rolled as a medium column. After simulation with paper, we find that the column will fall down in one direction. A small component is added to balance the force coming from the main part.

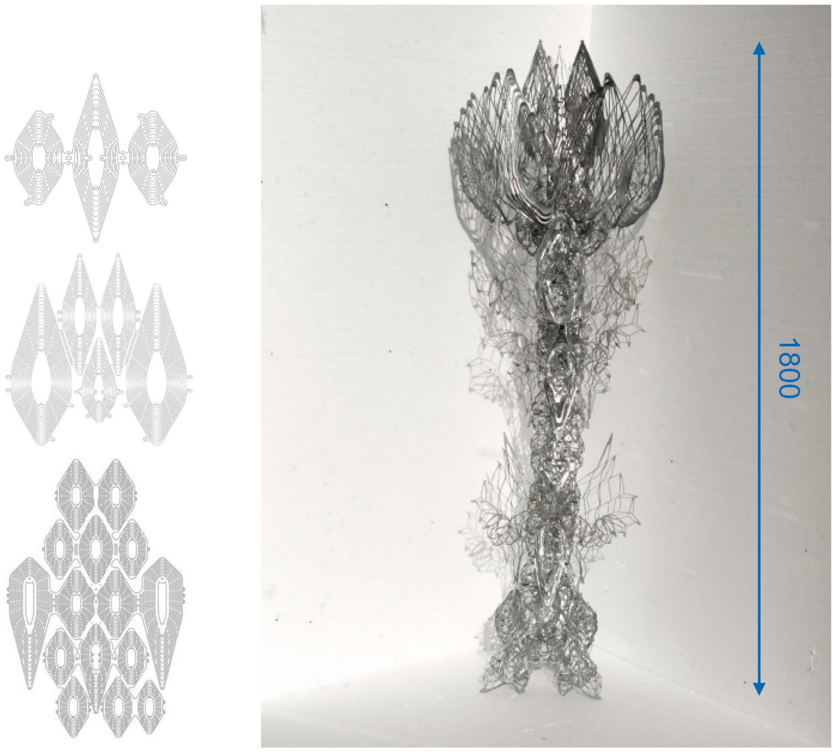


Figure 14. A column consisting of three pieces of multiple hexagon steel plates.

4.3. Casting

After the discussion about how to shape the skeleton for the reinforcement, the next step is taken, that is, casting. There are two primary ideas put into practice in this step. The research team considers putting elastic mesh material on the steel and pulling the steel plate into three dimensions. This idea is practiced through a simulation assisted by the software (Figure 15). The team also comes up with another idea, which is to put balloons into the three-dimensional steel structure, blow up the balloon, integrate it (closely) into the metal structure, and then pour the cement mixture into the balloon (Figure 16). Both ideas are found to be infeasible, and the team cannot pour casting material into the units according to the form of each unit. It is a waste of casting material, and the advantages of the unit pattern cannot be demonstrated.

Finally, the spraying craft is trialed (namely shotcrete) [18]. This column is produced by folding the interconnected laser-cut sheets of metal for gradual spraying, layer upon layer, with a mixture of the cement and water, which process is similar to that of ferrocement. Before adding PVA, only cement is sprayed, but it is not strong enough. Due to the difficulty in connecting concrete with the steel material, PVA is considered for addition into the concrete. After adding PVA, it shows a better performance. Before the cement mixture is sprayed, the ratio of cement, water, PVA is experimented on (Figure 17). The plaster is also experimented but found to be unfit for spraying together with cement, because plaster takes shorter time to dry, and it will block the spray tool.

Two columns are sprayed with different mixtures, as shown in Figure 18. The column in the foreground is sprayed with the cement mixed with water and PVA (its volume ratio is 5:2:1). The cement is sprayed on the steel and allowed to dry naturally (for around half an hour). Then, the cement is sprayed again (Figure 19) until the steel is totally surrounded by the cement mixture. The column at the back is sprayed without PVA. It illustrates the evolving relations of the two columns in terms of form and material (Figure 18). The column is made for around seven days (Figure 20).

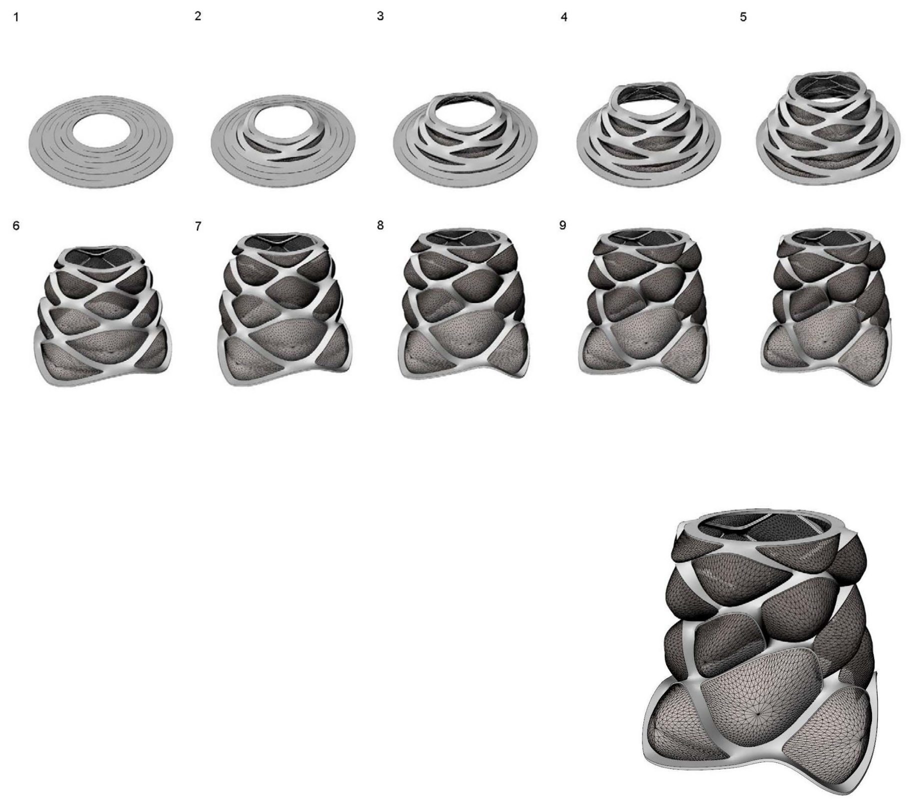


Figure 15. The simulation process (1–9) assisted by software: one possible method of casting with this shaping method.

Figure 16. A possible method of casting: putting the balloon into the steel structure and then pouring the cement mixture into it.

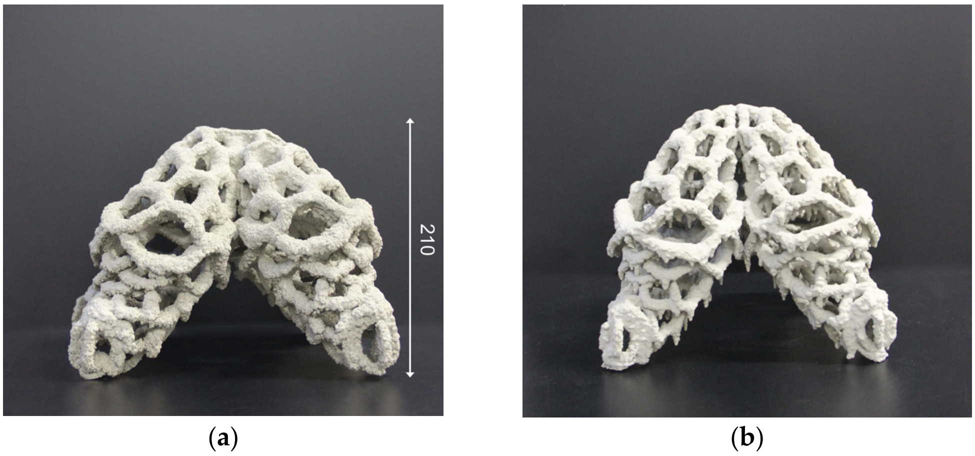


Figure 17. The experiment conducted on the ratio between the water: (**a**) PVA:cement = 2:1:5 (volume ratio); (**b**) plaster:plaster polymer:water:cement = 3:1:4:3 (volume ratio).

Figure 18. Two columns sprayed with different mixtures: the front one is sprayed with PVA and the back is not.

Figure 19. The process of spraying the cement (layer by layer) onto the steel skeleton, and the granular texture is shown on the surface of the cement mixture.

Figure 20. Photo of the ferrocement column.

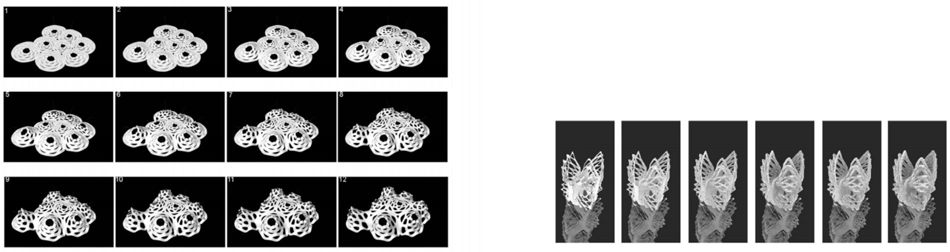
There are three advantages in spraying the steel structure with cement mixture. The first one is that the mechanical properties of the steel structure can be strengthened with layers of cement on it. The steel column is supported by the wooden frame for fixing while maintaining elasticity to some extent. When the cement is sprayed on it, it is fully fixed. Moreover, some points that are mechanically weak are sprayed with more of the cement mixed with PVA. This joint point is strengthened by the cement-PVA mixture.

The second one is that due to the relatively limited thermal resistance and corrosion resistance of the steel structure, the sprayed cement could protect the steel structure from damage caused by fire and water.

The third and last one is that the sprayed cement forms a textured surface on the ferrocement which is full of pellet, which reminds people of the Brutalism such as the Unit d'Habitation, Marseille, France, or the Barbican, United Kingdom. It is a "visual aspect" of the structure, enabling the aesthetic expression of ferrocement [19].

4.4. Design with the Digital Simulation

Regarding digital fabrication, digital tools are applied to export the shape directly through parameter analysis. In this research, digital simulation contributes significantly to shape design. It follows the fabrication processes, from the flat cutting pattern to the folding and spraying of cement mixture. As supported by the digital software of Rhino and Grasshopper, the process of shaping the single unit (including the form comparison) can be rapidly simulated. In addition, the force analysis of the designed structure can be simulated with Karamba, a plugin of the Grasshopper. The units are assembled into a furniture or an architectural element via Rhino. Through digital simulation, the spraying of cement mixtures is illustrated. It can be performed before physical experimentation, which prevents the errors in the direction for the shape-making research. With the assistance of this digital software, it is easy and fast to simulate the craft or real construction on the material (Figure 21). Moreover, the cost of experimentation is lowered significantly. The digital simulation can also be carried out after the research and shows the potential of using this fabrication into the architectural and urban design. For example, the scaling-up process of the units could be assembled via Rhino into such architectural elements as an urban furniture (via digital simulation).



(**a**) (**b**)

Figure 21. (**a**) The simulation of steel plate: the process of making shape with grasshopper. (**b**) This is the simulation of the spraying cement on the surface of the unit. It can be set as different thickness and different level of the texture of the spraying material. It is convenient to show that how it will look after spraying. The pictures show a quarter part of the simple column with cement on.

5. Discussion and Conclusions

In the present study, traditional material construction technology, such as ferrocement, is treated as a benchmark for the exploration into craft, not just for the development of novel designs. Through the potential of enhancement process, there are more possibilities opened up for this craft process. Different from the previous method of applying control on the shape through standard grid structure, the water jet laser cutting machine is used to create the designed pattern on the metal plate. Then, the metal plate is formed by pulling, folding, rolling and other methods, with cement reinforcement performed. The aim of this study is to explore the possibility of architectural "shape" from various perspectives such as form, material, and craft. The following is the most important findings of the research.

1. This research shows the potential of ferrocement on shape-making and fabrication. The steel sheet can become different 3-D architectural elements by cutting different patterns on it and assembling them in various modes.

2. The physical experimentation proved that this fabrication method has the potential to provide a strong way of structure, at least the three meters column can stand still. Moreover, in the column's project, the cement mixture is attached tightly to the steel surface, which strengthens the mechanical characteristics of the steel skeleton to prevent the steel material from corrosion.

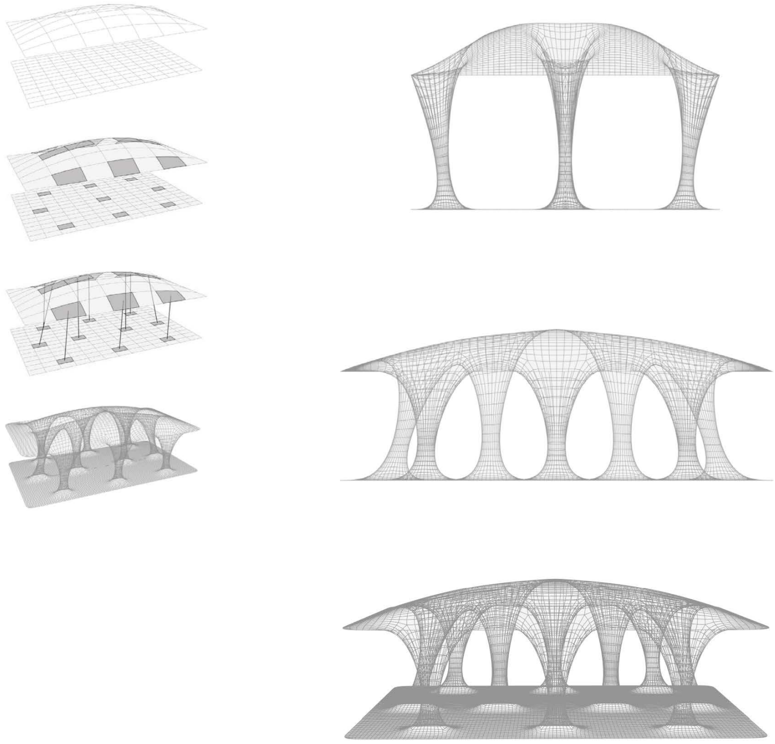
3. The research results have contributed to a prefabricated building method that facilitates assembly and prefabrication. All of the units of the steel skeleton are standardized and produced in advance via water jet laser-cutting machines. After the patterns are created out of the steel plate by cutting, even the students without any knowledge about construction can also learn how to bend them easily and assemble them into a skeleton quickly. The time cost is lowered compared with the wire mesh and it is easy to learn. This is the starting point for exploring the efficient construction of ferrocement.

4. In reinforced concrete, the reinforcement skeleton and the mold are different in our common understanding. The reinforcement skeleton is embedded into the concrete and the mold is at the periphery of the concrete. Moreover, the mold will be dismantled after the concrete is taking shape. In this research, the skeleton is used as both the reinforcement skeleton and the mold of cement, and it will be kept after the cement solidifies. This method could potentially avoid the consumption of mold and, in turn, save materials.

5. The research also demonstrates the effectiveness of digital simulation in improving, designing, and pre-controlling the fabrication, which provides an important perspective on "digital technology" in fabrication. With the assistance of initial computer simulation, the relationship between the pattern on the steel sheet and the final form is manipulated, and the conception of the structure is demonstrated, which may become important steps in the future prefabricated building technology.

6. This research result has a massive potential of application in architecture (Figure 22). Through digitally simulated rendering, it is demonstrated how the columns can be assembled spatially into a small pavilion (Figure 23). For the bigger size of the pavilion, the top and the bottom part can be bigger, and the numbers and the arrangement of columns suit the form that is needed. By this logic, the structure can extend easily, and the shape of the top surface still can be changed by different heights of the column. The column as a whole illustrates the transformation from bud to flower, showing the potential of change from a 2-D plane to 3-D structure, and the ceiling of the floor is generated naturally from the top and the bottom. This craft is applicable to the creation of an urban public space or a real building. This research indicates one possible solution to the shaping of the ferrocement, which marks the starting point of study on the relationship between shaping and cement mixture.

Figure 22. The possibilities of the different steel columns as assembled with the designed units, and the effects produced after they are sprayed with the cement mixture.



(a)

(b)

Figure 23. (**a**,**b**) are both of the simulation of a possible architectural/urban space created under this ferrocement strategy.

6. Research Limitation and Future Research Directions

There are several future research directions in the present study. (1) Although our physical construction shows that the column could stand still, the cement on the steels has improved the strength of the whole structure, and some simulation on the force distribution has been performed via Karamba of the circular steel unit (Figure 24). However, more rigorous tests are required on its mechanical property, and how to optimize the mechanical characters of this fabrication should be explored. The nature of this process would allow for topological optimization given the structural demands. Furthermore, a further improvement should be made on the software such as the Karamba on the simulation of the mechanical properties of concrete cement. (2) The research column is moved to another place for exhibition after the research. We find that most of the cement used on the structure is intact, but the cement mixture at the bottom part falls. This shows the weakness of the bottom part of the column and maybe it is because of the lack of bond. So, a future work suggestion would be the use of polymer materials as a partial addition to the mix. The use of polymers such as latex could promote the bonding to the steel skeleton. Moreover, more materials can be tested other than the cement mixture which could be sprayed onto the surface of the steel skeleton, to find out which mixture can be attached to the steel surface tightly.

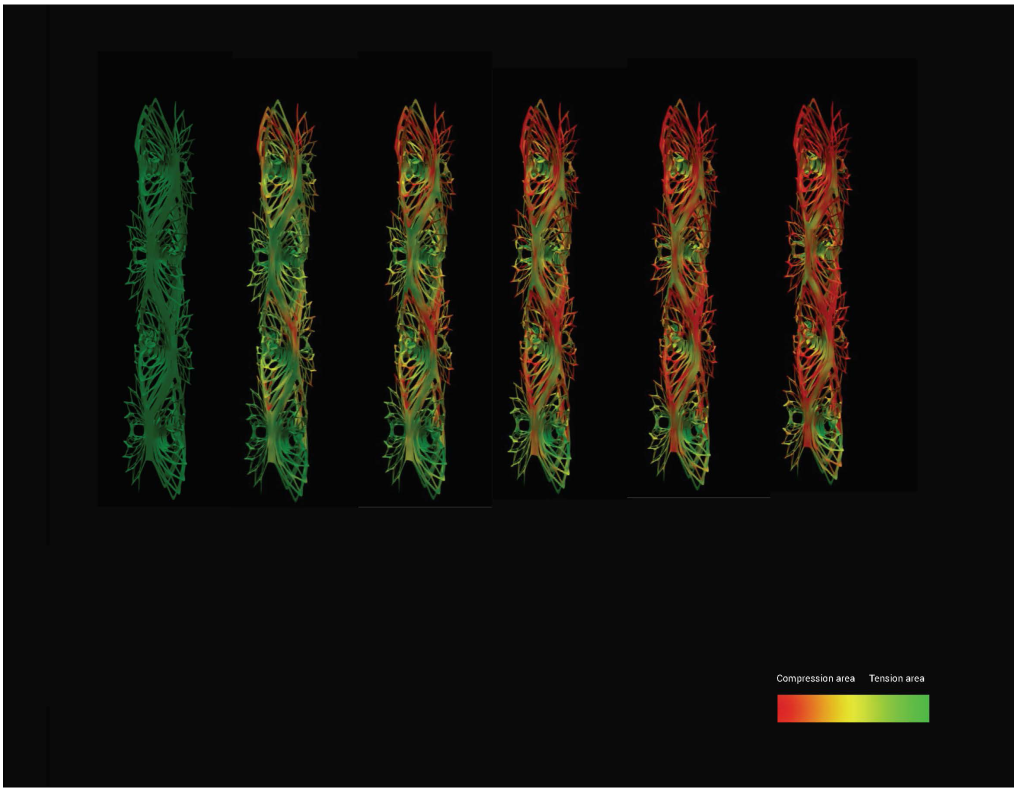


Figure 24. Force analysis on pulling process via Karamba. From the Karamba analysis, we could see that the garland on the column is useful to enhance the structure. As this rolling trunk is a symmetrical shape, it is stable. This is only a piece of sheet steel. After stretching and rolling the sheet, it changed to a column. When adding 200 kg weight on top of it, it will only shrink around 3.10 mm.

(3) A final direction is the tendency to assemble larger shapes with single units of similar type and different modulus. Supported by this assembly and prefabricated technology, customers could design and assemble anything they want under the guidance of open resources shared online. So, in this research, this trend is conformed, and the similar unit is designed, which allows customers to design and assemble them together as reinforcement on different scales, such as a chair or a column. From the perspective of materials, craft, assembling, form, structure and manufacture, some examples and key technologies are used to show how this method could be applied in the assembly by customers.

Author Contributions: Conceptualization, F.C., S.P. and W.Y.; methodology, F.C., S.P. and W.Y.; software, W.Y.; validation, F.C. and S.P.; formal analysis, F.C., S.P. and W.Y.; investigation, F.C., S.P. and W.Y.; resources, F.C. and S.P.; data curation, W.Y.; writing—original draft preparation, F.C.; writing—review and editing, F.C., S.P. and W.Y.; visualization, W.Y.; project administration, F.C., S.P. and W.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Kaish, A.B.M.A.; Jamil, M.; Raman, S.N.; Zain, M.F.M.; Nahar, L. Ferrocement composites for strengthening of concrete columns: A review. *Constr. Build. Mater.* **2018**, *160*, 326–340. [CrossRef]
2. Bramer, J. Is Ferrocement a Sustainable Option for the Construction Industry? Available online: https://www.amazingarchitecture.com/articles/is-ferrocement-a-sustainable-option-for-the-construction-industry (accessed on 7 November 2022).
3. Nenadović, A.; Tekić, Ž. Sustainability Benefits of Ferrocement Application in Composite Building Structures. 2018. Available online: https://www.researchgate.net/publication/326010966_SUSTAINABILITY_BENEFITS_OF_FERROCEMENT_APPLICATION_IN_COMPOSITE_BUILDING_STRUCTURES (accessed on 22 December 2022).
4. Mishra, G. Ferrocement: Advantages and Disadvantages in Construction. Available online: https://theconstructor.org/concrete/ferrocement-in-construction/1156/#Advantages_and_Disadvantages_of_Ferrocement (accessed on 7 November 2022).
5. Romualdi, J.P. *Ferrocement: Applications in Developing Countries*; National Academy of Sciences: Washington, DC, USA, 1973; pp. 14–15.
6. Romualdi, J.P. Ferrocement for infrastructure rehabilitation. *Concr. Int.* **1987**, *9*, 24–28.
7. Ibrahim, H.M.H. Shear capacity of ferrocement plates in flexure. *Eng. Struct.* **2011**, *33*, 1680–1686. [CrossRef]
8. Huang, H.; Huang, M.; Zhang, W.; Yang, S. Experimental study of predamaged columns strengthened by HPFL and BSP under combined load cases. *Struct. Infrastruct. Eng.* **2021**, *17*, 1210–1227. [CrossRef]
9. Ismail, M.; Shariati, M.; Abdul Awal, A.S.M.; Chiong, C.E.; Sadeghipour Chahnasir, E.; Porbar, A.; Heydari, A.; Khorami, M. Strengthening of bolted shear joints in industrialized ferrocement construction. *Steel Compos. Struct.* **2018**, *28*, 681–690.
10. Huang, H.; Huang, M.; Zhang, W.; Pospisil, S.; Wu, T. Experimental investigation on rehabilitation of corroded RC columns with BSP and HPFL under combined loadings. *J. Struct. Eng.* **2020**, *146*, 04020157. [CrossRef]
11. Hung, C.-C.; Chen, Y.-S. Innovative ECC jacketing for retrofitting shear-deficient RC members. *Constr. Build. Mater.* **2016**, *111*, 408–418. [CrossRef]
12. Hamidi, F.; Aslani, F. Additive manufacturing of cementitious composites: Materials, methods, potentials, and challenges. *Constr. Build. Mater.* **2019**, *218*, 582–609. [CrossRef]
13. Nuh, M.; Oval, R.; Orr, J.; Shepherd, P. Digital fabrication of ribbed concrete shells using automated robotic concrete spraying. *Addit. Manuf.* **2022**, *59*, 103159.
14. Maharashtra Engineering Research Institute. WRD Handbook Chapter No. 1 FERROCEMENT TECHNOLOGY. Available online: https://documents.pub/document/ferrocement-techno-handbook-on-ferrocementpdf-ferrocement-is-the-composite-of-ferro.html?page=4 (accessed on 22 December 2022).
15. Levada, F. Steel Fabrication and Its Appliances. Available online: https://levstal.com/what-is-steel-fabrication/ (accessed on 7 November 2022).
16. Mao, X.C.; Lin, H.Y. Study on sheet metal riveting processes and devices. *Adv. Mat. Res.* **2013**, *753–755*, 413–416. [CrossRef]
17. Woffinden, J. How to Make Concrete: PART 1—The Basic Process of Casting Concrete. Available online: https://jowoffinden.wordpress.com/2013/11/30/concrete-how-to-make-concrete/ (accessed on 22 December 2022).
18. Sakoparnig, M.; Galan, I.; Kusterle, W.; Lindlar, B.; Koraimann, G.; Angerer, T.; Steindl, F.R.; Briendl, L.G.; Jehle, S.; Flotzinger, J.; et al. On the significance of accelerator enriched layers in wet-mix shotcrete. *Tunn. Undergr. Space Technol.* **2023**, *131*, 104764. [CrossRef]
19. Naganna, S.R.; Ibrahim, H.A.; Yap, S.P.; Tan, C.G.; Mo, K.H.; El-Shafie, A. Insights into the multifaceted applications of architectural concrete: A state-of-the-art review. *Arab. J. Sci. Eng.* **2021**, *46*, 4213–4223. [CrossRef]