Feasibility study - Additional Research Project

Upscaling architected metamaterials for applications in civil infrastructure: auxetic lattices for confining concrete

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Upscaling architected metamaterials for applications in civil infrastructure: auxetic lattices for confining concrete

by

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1

Introduction

1.1. Context

From literature, it is accepted that steel rectangular confinement contributes to the strength and ductility of confined concrete [27]. However, would steel 3D re-entrant truss lattices be a better option for concrete confinement. From Tzortzinis et al. [29] it is becoming clear that the compressive strength increases remarkably by 140% and undergoes a ductile post-peak behaviour. Therefore, there is a lot of potential for this type of confinement. However, these lattices have been made on a small scale using Selective Laser Melting (SLM). Furthermore, how do we get from small scale to a larger scale? There are currently two approaches that have a potential for upscaling. Firstly, an approach which is called ”cooperative robotic fabrication”, in which robotics work together to fabricate spatial structures [23]. A second approach for upscaling lattices is called ”wire arc additive manufacturing (WAAM)” through robotics, where a technique called MIG welding is used [3]. Metal Inert Gas (MIG) welding is an arc welding process that uses a continuous solid wire electrode heated and fed into the weld pool from a welding gun. The focus in this report will be on the first approach.

1.2. Auxetic lattices

Additive manufacturing (AM) has known a steep increase of use in the past years, which is also referred to as 3D printing. The technique shows superior manufacturing efficiencies and is becoming more economically attractive. The downside of AM are the unwanted defects, such as surface roughness, imperfections, stress concentrations, deformations and porosity that are a result of the processing parameters, laser- speed and energy, powder thickness and anisotropic mechanical properties [8].

Auxetic materials are a new generation that have been coming to the market lately. This material, has a negative Poisson’s ratio and therefore laterally contracts under compressive loading. The topological architecture of a re-entrant lattice is key to define it’s auxetic behaviour [2]. In which re-entrant has the meaning of “directed inward” or having a negative angle [16]. Since auxetic materials are difficult to manufacture, because of their architecture. A new manufacturing technique, named SLM is introduced. This technique is used for higher melting products, like metallic and ceramic components. However, this technique is more expensive than Selective Laser Sintering (SLS). Besides that, lattices with overhanging geometries are difficult to manufacture, since the laser has more difficulty with heat conditions of new laid powder. Furthermore, horizontal struts are also difficult to lay [24]. Besides SLM also the SLS technique is used, which is for lower melting products like nylon.

Furthermore, Hao et al. made specimens using the Multi Jet Fusion (MJF) technique to understand the compressive properties of different architectures [12]. It is found that with all lattice reinforced specimens an increase in compressive strength is observed. Another method, which is rather similar but has a slightly lower quality surface finisher, fine feature resolution and less consistent mechanical properties is SLS [21]. Furthermore, this process is used to be able to fabricate parts, such as plastics, polymers and resins with a low melting point [11].

From literature, it is accepted that steel rectangular confinement contributes to the strength and ductility of confined concrete [27]. However, would steel 3D re-entrant truss lattices be a better option for concrete confinement. From Tzortzinis et al. [29] it is becoming clear that the compressive strength increases remarkably by 140% and undergoes a ductile post-peak behaviour. Therefore, there is a lot of potential for this type of confinement.

Besides this, the topology of truss-lattice materials is key to the performance of the concrete confinement. In a recent study by Gross et al. [10] research was performed on four different truss-lattice architectures. It shows that truss-lattice materials are more sensitive to defects when performed less-connected than more-connected counterparts. It is crucial to look into a topology with the least number of defects and the best mechanical properties.

1.2.1. Topology

In research, different topologies such as a hexagonal honeycomb and re-entrant hexagonal honeycomb are discussed using SLM [17]. It shows, that the auxetic properties of the lattice are proved and discussed. However, the goal of this research was not to look for an optimized architecture but to decouple the surface area and mechanical properties. Furthermore, in the research by Geng et al. other truss lattice architectures such as Gurtner–Durand, octet, octahedron, and tetrakaidecahedron were proven to be possible using two-photon lithography. The focus in this research is laid on the damage characterization of the architectures. It is confirmed that there is a big geometric error between the cad model and the actual product, there were different failures than predicted, like bending of the struts and higher stress concentrations being observed [8]. Finally, Besides SLM also a study using SLS is performed and more regular architectures such as: circular, octagonal, strengthened octagonal, RO (rhombicubactahedron), cubic and kelvin are discussed [12]. this study shows, that thermoplastic lattices also contribute to the mechanical properties of confined concrete. Besides this, all lattices contribute to a higher strength. Moreover, octagonal architecture performs best with a 71.36% higher strength compared to the plain concrete specimen. In figure 1.1 an overview is given of previously discussed architectures. In which, a division in positive Poisson's ratio- and auxetics are given.

Bow-tie

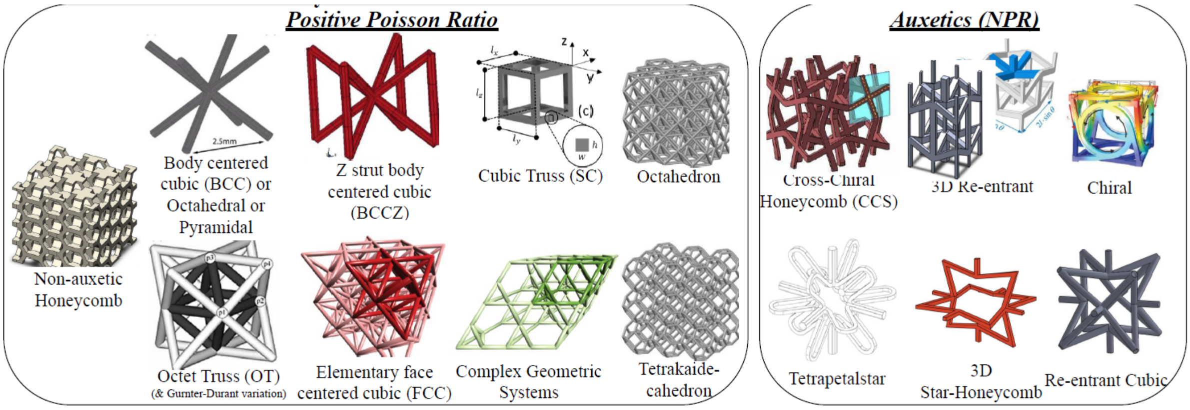

Figure 1.1: Geometric systems of 3D truss lattices [8]

Looking more in depth in the research of Georgios et al., a re-entrant architecture namely the bow-tie is used as confinement [29] . The potential of this architecture is showing good mechanical properties up to an increase of 140%. It is therefore also worth it to upscale this architecture to a conventional rebar size that is being used in practice. besides this, a picture of a recently created bow-tie lattice at UMass (University of Massachusetts) Amherst is shown in 1.2. It is worth mentioning that this lattice is still within its support structure. The following step is to remove support structure using EDM (Electrical Discharge Machining). The support structure is used to ensure a good quality of the print. From our experience and recommendations of the supplier, the quality of the print is severely worse with horizontal printed struts, because of local heat concentrations in the powder bed. In an angle the powder has more time to cool down before the next layer is applied. The study of lattice architectures is widened into different re-entrant angles namely 75, 80 and 85 degrees. Research is performed in understanding and comparing the different mechanical properties the different architectures have. Besides this, the research is followed up on using the architectures as confinement and having a good understanding of the composite action with concrete and its contribution to the mechanical properties.

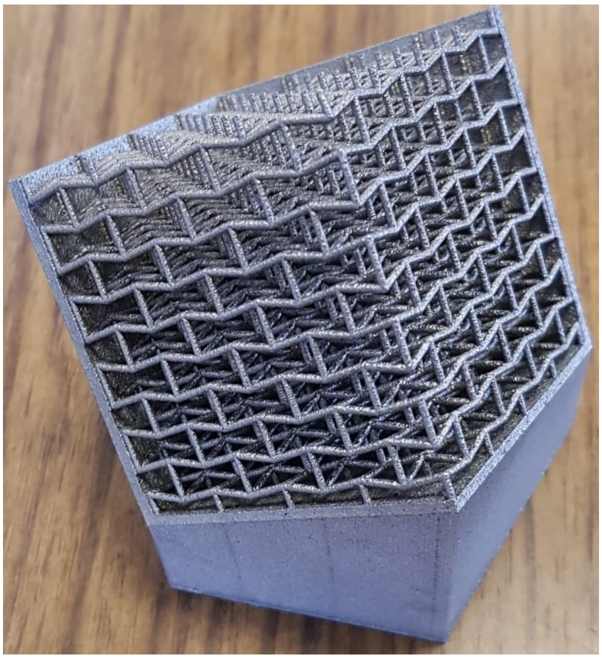

Figure 1.2: Re-entrant bowtie created using SLM

Double Pyramid

Furthermore, there is currently research being performed here at UMass in which the double pyramid architecture is also made using SLM. The double pyramid (DP) unit cells have been printed and their mechanical properties will be defined. The DPs are also created with different angles, namely 15/45, 15/60 and 30/48. Since the double pyramid has different angles the printer has a higher difficulty creating a good quality. Moreover, the lattices are printed under an angle and have a support structure. As a result, struts have to be printed almost horizontally, which is not desired for a good quality. Figure 1.3 shows a created unit cell using SLM and its supporting structure. Again to remain a good printing quality through the print. Since there are so many different printing angles it is even harder compared to the bow-tie to maintain a good printing quality.

To conclude, the focus in this report will be on the two architectures presented above. Moreover, for simplicity reasons one angle per lattice is chosen to start with. These lattices will be upscaled and fabricated using robotics.

1.2.2. Upscaled bow-tie

In figure 1.4 an upscaled bow-tie is presented, which is manufactured recently in a collaboration with UMass and Toggle. In the left picture, a full scale unit cell is shown. This consists of several separate steel bars that are connected using welds. before performing the welds, the outer parts of the unit cell are constructed. These are the corners consisting of three separate bars. This is followed up by creating the tree in the middle, consisting out of five separate bars. After which, the full top part is manufactured using a weld between the corner components and the middle tree. This process is then repeated for the other side. Finally, the top- and bottom part are connected to create the full unit cell.

Figure 1.3: Double pyramid architecture created using SLM

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Figure 1.4: Upscaled bow-tie manufactured by Toggle [26]

1.3. Problem

As mentioned before there are two approaches that have a potential for upscaling. In collaboration with Toggle (Toggle.is) the lattices will be fabricated. But how can the lattices be fabricated and what challenges are laying there ahead? Once fabricated, the lattices are up for testing. So, under compressive loading what kind of failure modes, imperfections and mechanical properties of the lattices can we expect? Also when looking at different architectures of lattices, such as the tetragonal re-entrant bow-tie and double pyramid which differences can be observed? Currently, research is also performed on these two types of lattices and what their contribution can be as confinement for concrete. on a larger scale the same question would arise. How would the bonding of the lattice be between the steel and concrete and what contribution does it have?

1.4. Goal

The main goal of this research is to give a further understanding on the upscaling of auxetic lattices as confinement in concrete. Therefore, a study is performed on the protocol that is used to manufacture a lattice and work approach to control the robots. Furthermore, a first set up for the parametric design is performed, including a design of the re-entrant bow-tie and double pyramid architectures. Finally, a preliminary computational study is performed in ABAQUS.

- **feasibility study:** Define a clear feasibility study on the potential on the upscaling of architected lattices.

1.5. Research questions

In order to reach the goal of this feasibility study, there are listed several research questions that are answered in this report below. The research questions are answered using literature, expert opinions and recently performed research at UMass.

1. What robotics have already been used for construction?

2. What protocol could be used to manufacture upscaled auxetic lattices?
3. What work approach is used to control robotics?

Figure 1.5: Example of an assembled structure by robotic arms [23]

2

Literature review

In this chapter the literature related to robotics is discussed. Furthermore, the literature is used to have an understanding in what position the industry currently is. The focus of the literature study is on the following:

- **Robotics in construction:** which relates to robotics that have already been used in construction.
- **The work approach to control robotics:** to understand the protocols that have been previously used to control robotics.
- **Parametric design methods:** to understand reasoning on using certain methods of designing and what in- and output it generates.
- **Multi-robotic fabrication** which shows reasoning for using multi-robotic fabrication and its benefits.

To conclude, the main points from the literature review are summarized and discussed for further use in this report.

2.1. Robotics in construction

It is concluded that conventional construction is reaching limits in terms of performance, growth, defect rates, etc. A new state of the art innovation would be the use of robotics in construction. However, since we are at the beginning, the involvement of robotics currently is rather low when comparing to the automotive industry where it is fully automated [4]. It is becoming clear from figure 2.1 that the construction industry is falling behind in terms of productivity. While the automobile industry is stepping up in automation of process, the construction industry tends to remain the same. While in the 90's robot development was very strong, the focus in recent years is focused on virtual reality, monitoring using sensor-based equipment and tracking. Looking into the future, there is a lot of potential in digital fabrication. Combining design- and construction processes into a tight planning, makes it a very efficient way of working [9]. Another reason would be having a reduction in accidents, reduced waste and increased efficiency of material. However, it is mainly the final step of assembly that is performed by manual labour. Moreover, combining stagnation and technical limits in construction and comparing that with new developments, initiations and technologies there is a relationship visible [5]. besides, it is also stating some key points when realising a fully construction automated process, which contains: " 1) robotic design, 2) robotic industrialization, 3) construction robots, 4) site automation and 5) ambient robotics". From [7] et al. we learn that the construction of modular homes were first created using robotics arms.

2.2. Work approach to control robotics

In this part, the general work approach that is used to set the robotics from start to end is discussed, to be able to start fabrication. From literature different approaches to manufacture a space frame using coorperative robotics are described. [7] Bruun et al. prescribes a method, using a rigid theory that

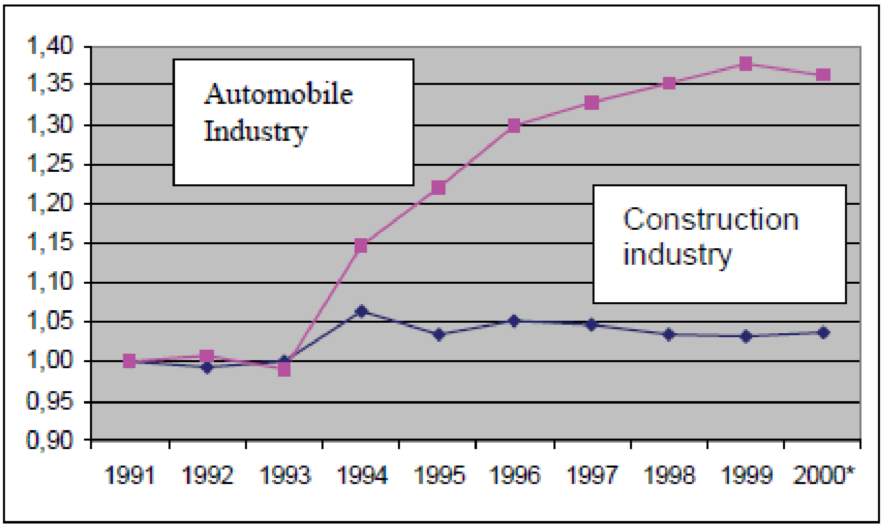

Figure 2.1: Productivity of the construction vs. automobile industry [4]

ensures stability of the structure throughout the whole fabrication process. Furthermore, it gives ideas on both the assembly and disassembly processes regarding: path planning, constraints, support conditions and preventing collisions. Besides this, [14] Huang et al. are proposing methods for the necessity of robotic modeling and planning by combining assembly description, sequence, process flowchart, and robotic set up a plan skeleton is defined. In this plan skeleton, the ideas from multiple designers are gathered and compiled by an algorithm. To plan the movement of the robotics another linear and non-linear algorithm is used to define the motions of the robotics. Finally, the work is demonstrated by manufacturing a real-scale timber structure. Another work protocol is defined in research by Kumar et al.[18]. The research is using a single dynamic motion robot that is used to manufacture unconventional concrete applications. The work approach using robotics is described step wise in chapter 3.

2.3. Computational design methods

Setting up the lattice is computationally performed using Rhinoceros 7, the differences in angles and rebar sizes gives a good reason to set it up parametrically. Creating a parametric design tool contributes to the physical and digital implementations according to the assembly sequence of the structure. Furthermore, information about limitations, strength of the system and path planning shows an overall feasibility of the structure being made. in figure 2.2, a design process is illustrated. The figure starts with indicating an input definition of the full geometry and the sequence that the robots have to follow. Secondly, a typology per added element is shown, followed by an structural optimization, to maintain stability and structural performance. Finally, the fabrication data that is followed from all previous steps is generated. In our case, the topology of the lattice is decided beforehand, but the sequence in which the lattice is fabricated is yet to be determined. Following the order of the figure, the following method can be followed for the fabrication of lattices.

Input definition

To feed the robotics with the geometry a parametric design method can be followed. For example a method using Rhinoceros 7 where the geometry of the lattices is defined. The following input parameters would be necessary to create the model:

- Angles of the struts
- Strut diameter
- Strut length
- Number of unit cells in X,Y and Z direction
- Type of lattice/architecture
- Center-to-center distance between the unit cells.

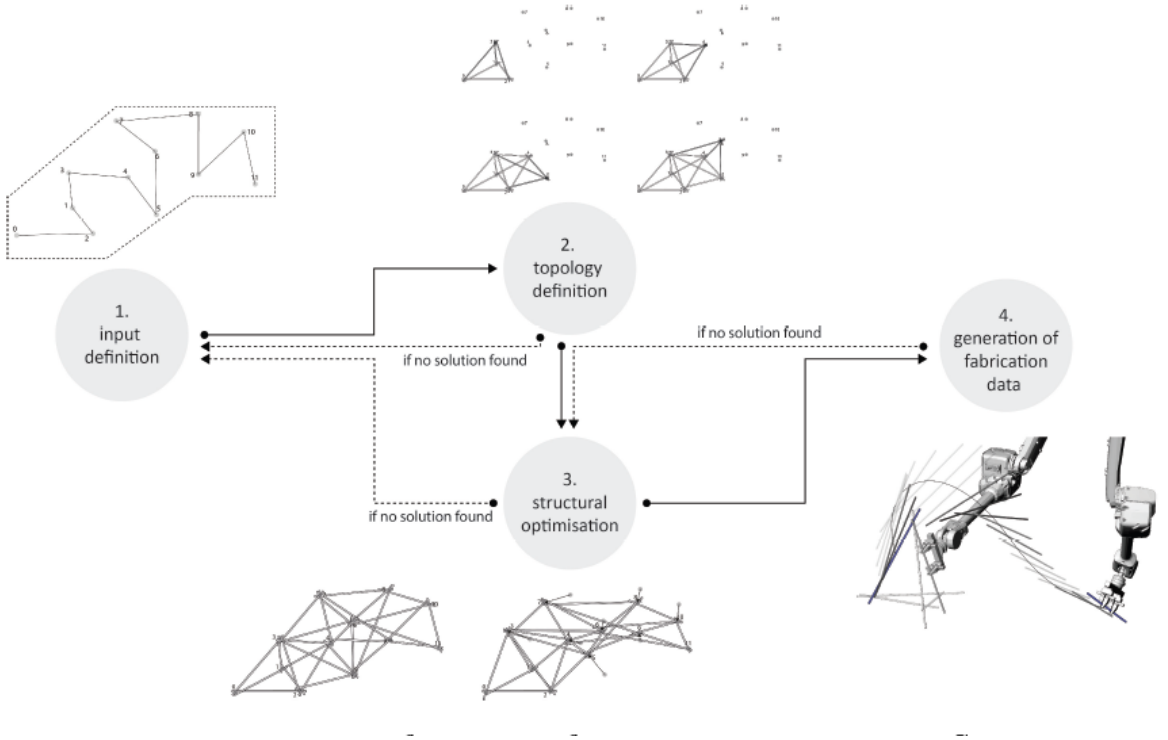

Figure 2.2: Computational design proces [23]

In Rhinoceros 7 the parameters can be continuously changed to understand the influence and behaviour of each parameter.

Topology definition
The in section 1.2 shown lattices are already specific topologies that have proven to be auxetic. The order in stacking the rebar in to a full lattice is yet to be unknown. Furthermore, to maintain stability of the lattice during manufacturing a sequence for the robot to place the rebar needs to be developed.

Structural optimisation
As previously mentioned the re-entrant bow-tie and double pyramid lattices can vary in angles. Current research performed at UMass on small scale lattices, show that the Poisson's ratio can change drastically when using different angles [29]. To maintain simplicity for fabrication reasons we firstly focus on a 85 degree bow-tie and 15/45 degree double pyramid lattice. One of the future goals would also be to make the fabrication versatile to be able to change between designs.

Generation of fabrication data
Finally, the data gathered information from the previous steps is necessary to obtain solutions for the robot to fabricate the lattice. As figure 2.2 is also indicating, there is a continuous link between steps to optimize the system.

2.4. Multi-robotic fabrication

Combining multiple robots leads to an advancement in possibilities of construction, while one robot holds an item the other robot can perform tasks on it. Having an increased speed in construction and a higher precision, shows high potential for further research. In recent research, a spatial structure is designed and manufactured using multi-robotic fabrication [23]. The research has shown that the robotics have created a spatial structure with good structural behaviour, flexibility and quick fabrication using manual welding. Furthermore, while fabrication there is no need for additional supporting. Besides this, there are additional factors that are involved when using multiple robots. For example, there is a limited workspace, possibility of collisions, necessary path planning and solution space to complete a successful fabrication process. It is concluded that defining path planning for the robotics shows high iterations to solve and difficulties in integrating the design process, because of the low speed of the calculation. Finally, a communicating information flow needs to be set up between the fabrication processes and constraints of the design.

Following up on communication of data between different sources, there are many open source Rhinoceros 7 plugins that are available on Food4Rhino (https://www.food4rhino.com/en). To name a few, there is ”HAL Robot Programming & Control”. This plug-in helps to set-up robot processes to feed the geometry of the designs to the robot. Moreover, you are able to choose any robot that you have available at your fabrication hall and make it perform the commands you desire. Some commands that are interesting to plan are: the motion of the robot, the procedure in which the robot is performing tasks and to show a simulation of the feasibility to perform the tasks for the robot [25]. Besides HAL, there is Taco, which is also an open source plug-in from Food4Rhino. Taco is more elaborate on the actual robotic commands that the robot has to perform. For example, grabbing or moving an object. Besides, it also has features similar to HAL, like the motion planner and simulation the robot has to perform [30].

Besides Rhinoceros 7 plug-ins, there is also COMPAS FAB Framework. COMPAS is a Python based library that covers a wide field of applications. Some main applications are geometry, data structures and robots [19]. Furthermore, the use of COMPAS has proven to be validated by several state-of-the-art projects at ETH Zurich. These project include: DFAB House, HiLo Roof Prototype, MeshMould, Knit Candela, WEF Floor, Concrete Choreography and HiLo Roof. To conclude, this shows another method to fabricate structures using multi-robotic fabrication.

2.5. Conclusions

In this chapter a first study on literature is performed to help us understand how to use robotics in the upscaling of auxetic lattices. The following key points are obtained from this chapter:

- The construction industry is behind on productivity when comparing it with the automobile industry. There are several reasons like: safety, productivity, performance, etc. to use robotics in construction.
- There have been multiple examples of robotics that have been used in construction.
- There has been a different focus for the construction industry in terms of R&D, this has mostly been in virtual reality, monitoring using sensor-based equipment and tracking.
- Literature is showing different work approaches to control robotics, but all seem to be able to remain stability and have a solution for the case study to succeed.
- Rhinoceros 7 is a powerful tool that is worth using to parametrically set up the design of the lattices.
- A design process in 2.2 suggested in the research of Parascho et al. [23] is a clear and constructive way to set up a parametric design.
- There are several plugins, such as: HAL Robot Programming & Control and Taco that help multi-robotic fabrication. Besides, there is COMPAS FAB Framework that is a Python code based framework for a wide range of applications, including geometry, data structures and robots.
- Increasing productivity of robotics is achieved by multi-robotic fabrication. However, the complexity of fabrication increases drastically. A clear work approach should be defined.
- There are many open source plug-ins for Rhinoceros 7 that help modelling the design and correctly defining the input to control the robots.

3

Robotics

In this chapter, a deeper understanding of the working methods and protocols using robotics is presented. Furthermore, there are several topics that are discussed:

- **Geometric system:** this indicates the conditions that have to be met for the system to perform as an auxetic lattice.
- **Cooperative robotic fabrication:** this resembles all the necessary processes that have to be met for the robotics to manufacture the lattice.
- **Material system:** this indicates the material that is being used for the lattice.
- **Parametric design:** in order to make quick changes a parametric design is made.
- **Computational design:** a preliminary structural analysis using ABAQUS.

Finally, a short conclusion is presented on how the system, processes, material system and design influence the end result of the lattice. To be able to maintain a good experimental specimen all conditions have to be met.

3.1. Geometic system

From chapter 2 it is becoming clear that robotics can contribute to new fabrication methods for civil engineering purposes. In our case we are referring to a re-entrant bow-tie and double pyramid system, which has an auxetic behaviour. Moreover, to able to fabricate the lattice, the connections and bar positions of the lattices have to be defined. This ensures that the lattice maintains stable during production. Besides, support structures need to be designed for the rebar to keep the correct position during welding.

3.1.1. Connection

Following up on the previous section, the fabrication of the lattices depend on the architecture being made. For example, the pieces are different in length and the ends of the bars can be cut under an angle. In the Brack lab at UMass Amherst, the first bars of about 60 mm are created using a metal cutting band saw of 10x16 inch (254x406x4 mm). in figure 3.1, the result is shown of the small pieces that have been cut perpendicularly. The surface of the cut rebar is showing great quality and the length of the pieces are all equal. This means, the machine seems cut for the job to do the upscaling for the full lattices.

As mentioned, the current bars are cut perpendicularly. As a result, the connection between the bars becomes more difficult. This is because the bars are placed under an angle to ensure the auxetic behaviour of the lattices. Fortunately, the machine is able to cut rebar under an angle too. Besides, an optimization must be found in collaboration with Toggle on how the welds can be performed in the most optimal way and with the least amount of labour. Since, the bow-tie architecture has 810 nodes and the double pyramid architecture has 605 nodes per lattice. Each node consists of several connecting rebar pieces, which all have to be connected.

A final option would be to use a bending machine or tool that can save a lot of cuts and welds, besides it would save a substantial amount of welding material. This means, costs and labour could be reduced drastically. Since bending machines are expensive, another option might be to create a simple bending tool ourselves in the lab. In a video by Er. ABJIT an idea for a simple bender is shown [1].

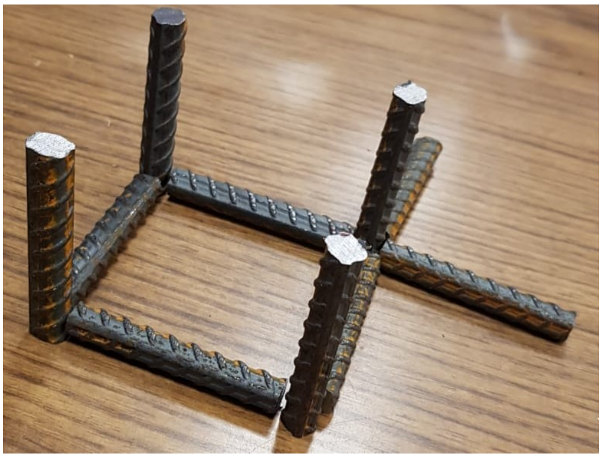

Figure 3.1: Cut rebar at Brack lab

3.1.2. Bar position

To place the bars in the correct position, steel plates will be made to also ensure a temporary support. While the robotics perform the movement of the steel a third robot will ensure the welding of the bars. In figure 3.2 the layout of the several bar is shown, each bar is placed in the correct position and then welded manually for now. Being further in the process the goal is to use robotic welding as much as possible.

3.1.3. Support structures

Furthermore, figure 3.2 is also showing the support structure made by Toggle. The order in applying the support structure is critical for assembling the unit cell. The support structure consists of several small steel plates that have dimensions according to the unit cell that is created. Besides, since the bars are under angle to create the auxetic behaviour part of the steel plate have to be diagonal too. Finally, since residual stresses occur during and after welding, the bars need to be clamped to remain on their position.

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Figure 3.2: Support structure manufactured unit cell [26]

3.2. Coorperative robotic fabrication

For the fabrication of the lattices we partnered with a company called Toggle. Toggle is one of the leading companies in automation of optimizing rebar assembly for construction. Together with companies in the construction field they have manufactured prefabricated rebar cages that can be used for columns in highrises. Furthermore, Toggle is using cooperative robotic fabrication to be able to automate their products. For manufacturing the architected lattices the facility of Toggle is used. Together with Toggle an approach to manufacture the lattices is worked out in the sections below. ABB robots are used for fabrication, which is a well know brand in industry delivering robots.

3.2.1. Assembly method

In research by Bruun et al. [7] a mathematical rigid condition is prescribed to keep the structure stable during fabrication. In this research, two robots are used where they continuously switch function by placing a bar or holding the structure. Moreover, the geometry is defined in such a way to create tetrahedron shapes to maintain a structurally rigid structure. Besides this, in a case study performed by S. Parascho another structure using robotics is defined [23]. Also in this research, a tetrahedral configuration is used to ensure structural stability. While the robots either hold or bring a next aluminium bar, the connection is manually welded.

Furthermore, another way of assembly is by defining a full plan skeleton [14]. In this plan skeleton, all steps per construction step are defined and visually shown. In Annex A.1 the plan skeleton is given, which is used to perform one construction step. It is clearly visible, that each different motion has to be carefully planned. Each action, represents multiple movements either by the robot or clamp in order to be successful.

Another protocol is presented in figure A.2 by research of Kumar et al. [18]. In this research an unconventional concrete shaped wall is fabricated using robotics, like shortly discussed in the previous chapter. Firstly, a so called Transmission Control Protocol/Internet protocol (TCP/IP) model is built, which allows control of the overall building process. Furthermore, a division is made between the robotic arm and the robotic end. Both of them are also controlled by two different software, namely Arduino and an ABB controller software. As the figure is stating, the robotic end has several small task routines, which are controlled by Python. Them working together results in the functioning of the robotic end effector. Separately, the ABB controller is also controlled with Python and then modelled with Robot Studio. Finally, Grasshopper for Rhinoceros is used to run simulations to monitor the execution of commands.

3.2.2. Tolerances

The assembly method is closely related to the tolerances that have to be achieved. For example, the sequence in which certain bars are connected is leading to where the tolerances have to be met. The steel bars are cut on their correct size and welded afterwards. There are several articles stating the tolerances that have been dealt with. in the research of Parascho et al. [23] deviations to approximately 5 mm were measured. Several reasons are being stated: imperfections of the aluminum bars, minimal adjustments of the robotic set-up and the small deviations in the coordinate system that is being used. Furthermore, in research by Giftthaler et al. a maximum assembly error of 7 mm was achieved [9]. Besides this, the robotic tolerance in the research by Eversman et al. was kept lower than 1 mm. Moreover, because of the consistent tolerance it was observed during construction that the longer elements led to issues, while cutting and assembling of short elements were more difficult [22].

3.2.3. Pick-up procedure

Depending on the task the robot is needing to perform, a so called pick-up procedure must be followed. There are two general pick-up procedures, namely a stationary and dynamic pick-up procedure. As the names are implying, the stationary procedure is defined as one where the robot gantry does not have to move material but it is picked up from a fixed location. Another option, would be to give the material manually to the robot, which implies dynamic. Sensors could be used for the robot to determine it's location, where the ground is used as reference position [23].

Using robotics to fabricate the lattices is possible in many ways, such as the welding of the several connections, holding and placing the rebar pieces or keeping the overall structure stable. However, defining the algorithms for the use of the robot are complex and extensive. Therefore, a decision based on time, labour and resources must be made. Since, it is expected that the design and manufacturing process changes. Manual actions will remain needed for the fabrication of the lattices at first. As more lattices will be manufactured the use of robotics can also be expanded an optimized.

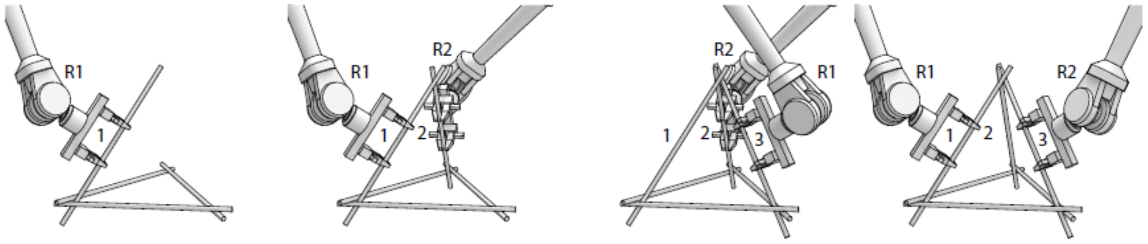
3.2.4. Gantry movement

From research by dorfler et al. it is becoming clear that "Optimal Control" can be used to optimize the criterion and to set-up a control policy for a dynamic system [9]. Depending on the scale of the structure manufactured gantry movement is necessary [23]. Since the arm of the robot in this research is not able to reach all necessary positions from one point, gantry movement is necessary.

The architected lattices that are designed for this research have an approximate size of 0.5x0.5x0.5 meters. Therefore, each action of the robot can be performed from on point and gantry movement is excluded. In Appendix B the designs of the bow-tie and double pyramid lattices are shown. The drawing shows overall dimensions and contains a description containing general information about the lattices.

3.2.5. Robot assignment

Besides the pick-up procedure, the geometry, size of the structure, fabrication technique and strategies also the influence of the robot assignment is crucial. In the research by Parascho et al. a three bar group is used and expanded to a full structure, will the robots help supporting the structure. In figure 3.3, a robotic assignment is shown, while completing a three bar group. Each robot is given predefined assignments on which bar it needs to hold. Another point of attention, is the reachability of the robot. For example, when a certain robot is holding an element, the other robot should be able to reach the desired location with his element. The research is also stating to predefine the space that robots have, help the robots find a reachable position [23]. Moreover, it is a continuous process to find a proper solution, which could mean making changes in the gantry movement, path planning and robotic assignment. As result, the process can be made more flexible, with a reduction in possible collisions. In our research, robotic welds are included in the fabrication process. This means, all possible locations where the robot has to weld need to be defined beforehand. Besides, what are the options in holding rebar by the robots.



1 = R1 or
1 = R2

1 = R1 : 2 = R2
1 = R2 : 2 = R1

3 = R1 or
3 = R2

Figure 3.3: Robotic assignment [23]

3.2.6. Path planning

Depending on the robots that are assigned for the task, see the previous subsection, a so-called path panning needs to be defined. Starting by dividing two main categories of movement, which are static and dynamic. Mobile construction robots have several challenges, which could be: motion constraints, obstacles in the construction area, different contact areas and related forces and finally the uncertainties of the model [9]. Furthermore, the article is stating several optimal control algorithms, like standard integrated planners, Rapidly Exploring Random Trees and Probabilistic Roadmap methods, that could be used to help overcome these challenges. Besides this, for mobile construction robots base- and arm motion can be separated or controlled jointly. This is convenient because, when focusing on building

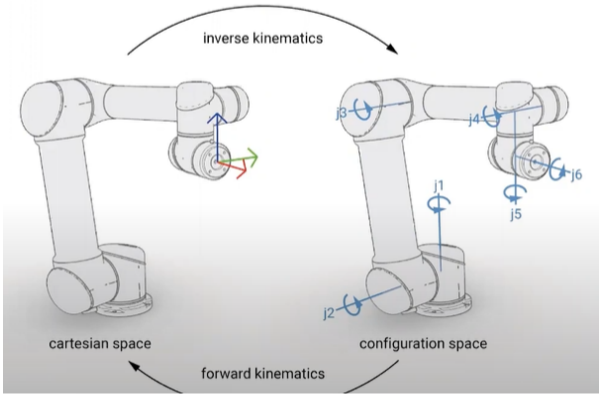


Figure 3.4: Kinematics between cartesian and configuration space [31]

tasks the focus is on the arm motion. This simplifies the algorithm drastically [6].

As mentioned in chapter 2, simulations can be used to perform checks on the path that the robot is going to follow. Moreover, an integrated system should be designed to combine the path planning, control frame work and the simulation. Grasshopper for Rhinoceros 7 is software plugin that can be used to this integration [18].

Following up on static movement, there are again two categories that are defined in research by Parascho et al. [23]. Namely, manual- and automatic path planning. Firstly, in manual path planning, where a center point is defined, where around all possible geometry configurations are modelled to create a sphere. However, the method is discarded in the research, because the interaction method doesn't guarantee a solution and has to be manually adjusted. Therefore, the second option comes in place, which is automatic path-planning. As mentioned before, a Python based library COMPAS-FAB is used to develop an environment for fabrication or design of a generated structure. In figure 3.4 a clarification is given of what is meant with forward or inverse kinematics. It is a way of calculating the movement a robot is making. Forward kinematics is defined as: "Foward kinematics utilises each joint's value and applies this to the kinematic model of the robot to calculate the resulting pose of the TCP. Conversely, inverse kinematics takes TCP pose as input and reverse calculates each of the robot's joint value" [23]. Of course, there are several solutions which could be possible. Therefore, collision-free configurations should be simulated and adapted accordingly. Moreover, an optimization could be performed to find the least costly or time consuming option. The following parameters could be reasons when a path is not found:

1. Data coming from the path-planning algorithm.
2. The number of configurations of the model to have a correct model.
3. constraint of axes limits.

Another group of reasons is related to the geometry or design parameters:

1. The sequence in which objects are placed.
2. How the robot's are assigned.
3. How the robot is oriented at the insertion pose.
4. Where the gripper pose is located.
5. The overall geometry of the structure being manufactured, which consists of nodes in space.

Besides this, in the research of [13] a suggestion to optimize speed and success rate of the robotic process is given. As stated, it is possible to input robot configurations while running the program. As a results, the robot can be guided and its speed increased for the targets that are hard to reach. The COMPAS RRC library is used to plan and compute the kinematic paths of the robot beforehand.

3.3. Material system

As the introduction is stating, the topology of the lattice is in close relation to the mechanical properties of the system. Therefore, two types of architectures are chosen, which have proved to be auxetic. Moreover, the bow-tie and double pyramid are chosen in this research. The bow-tie and double pyramid lattices are made of conventional #3 and #4 number rebar. This means all material properties of the rebar are known and can be used for the understanding of the behaviour of the lattices. Besides rebar, conventional welding is used to create the connections between the rebar. The properties of the rebar and welds are presented in this section.

3.3.1. Rebar

In order to manufacture the lattices an order is placed at Harris Rebar (https://www.harrisrebar.com/). The following calculation is made to determine the rebar, which is sufficient to produce about 3 lattices per rebar number and per architecture. An overview of the numbers is presented below, the properties are presented in Table 3.1:

- Bow-tie (85 degrees) –> 4x4x5 unit cells
  - number #3 rebar with 3 lattices = 1134 feet (345.6 meter)
  - number #4 rebar with 3 lattices = 1449 feet (441.6 meter)
- Double Pyramid (15,45 degrees) –> 5x5x4 unit cells
  - number #3 rebar with 3 lattices = 1194 feet (364.8 meter)
  - number #4 rebar with 3 lattices = 1635 feet (499.2 meter)

Some other specifications of the rebar are presented in the table below:

Table 3.1: Properties rebar [28]

Imperial Bar Size	”Soft” Metric Size	Weight per unit length (lb/ft)	Mass per unit length (kg/m)
#3	#10	0.376	0.561
#4	#13	0.668	0.996
Nominal Diameter (in)	Nominal Diameter (mm)	Nominal Area(in^2)	Nominal Area (mm^2)
0.375	9.525	0.11	71
0.500	12.7	0.2	129

3.3.2. Weld material

Besides the rebar, a conventional weld material is used to connect the bars together. The mechanical properties of a conventional material are presented in table 3.2. Some factors to think about before applying the weld will be: the amperage and voltage of the MIG welding machine, the diameter of the wire and the wire feed speed. Besides, for the auxetic system we need to ensure a good connection between the bars to maintain the auxetic behaviour. Furthermore, undesired imperfections could lead to local failures of the struts.

In the table below, some general properties of a weld material are presented. As the table is presenting the yield strength which is higher than conventional steel, which is desirable to prevent local failures in the connection. However, this is in close relation to the thickness that is applied for the connection. Besides, the tolerances achieved in the previous subsection, should also be taken in to account for the welds that are being applied. Finally, to simplify the process first, manual welds can be performed for the first cages. After understanding the behaviour of the lattices, an optimization can also be performed on how to apply the correct welds.

From Toggle, we understand that Toggle is in possession of two small welders, the Lincoln 110V MIG welder and a Harbor Freight 220V MIG welder. They can use any MIG wire, therefore a MIG welder can be ran on anything from 98/2 argon & CO2 down to 100% C02.

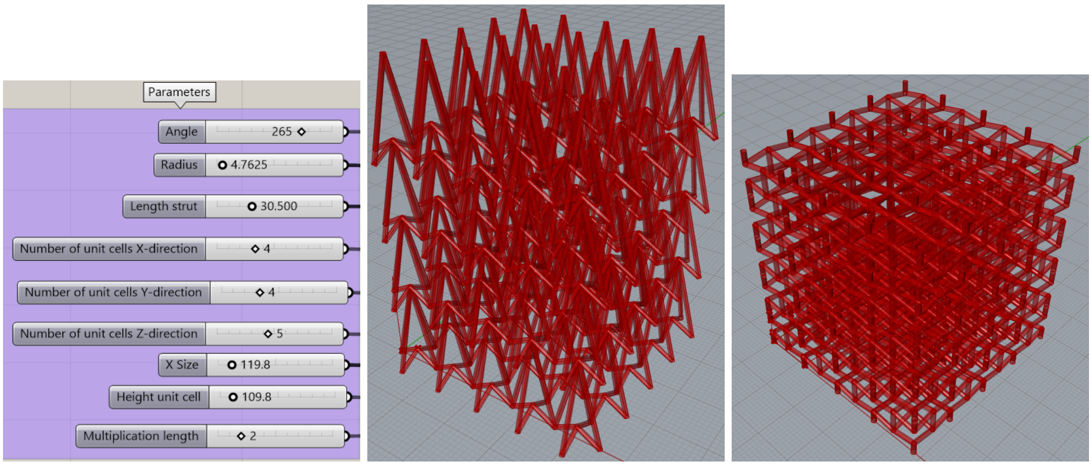
Table 3.2: Mechanical properties weld material [20]

Mechanical Tests	100% CO2	AWS Spec
Tensile Strength	81,000 psi (556 MPa)	70,000 psi (483 MPa) Minimum
Yield Strength	66,000 psi (452 MPa)	58,000 psi (400 MPa) Minimum
Elongation % in 2” (50 mm)	27%	22%

3.4. Parametric design

The modelling of the geometry of the lattices is performed using Rhinoceros 7. Following up from section 2.3 regarding the input definition, a list of parameters is presented. In figure 3.5(a) these parameters are presented, by simply sliding the bar the values can be changed. Moreover, while changing values the model also continuously updates. In sub-figures (b) and (c) the different architectures are presented that have been modelled using Rhinoceros 7. The goal of these models is to quickly do a feasibility study of the parameters and to generate the geometry of the model, which can be shared among each other.

Furthermore, for preliminary structural analysis the plug-in Karamba3D [15] could be used. Just like the previously mentioned plug-ins it can be added in Grasshopper for Rhinoceros 7. Karamba3D, enables interactive analysis & calculation, evolutionary structural optimisation and genetic algorithms & multi objective optimisation. For now, ABAQUS is used to perform the structural analysis. But, Karamba3D will be very interesting to use when the research is being extended towards different architectures and topologies. To simplify things first, we stick to 85 degree for the bow-tie and 45/15 degree for the double pyramid architecture.



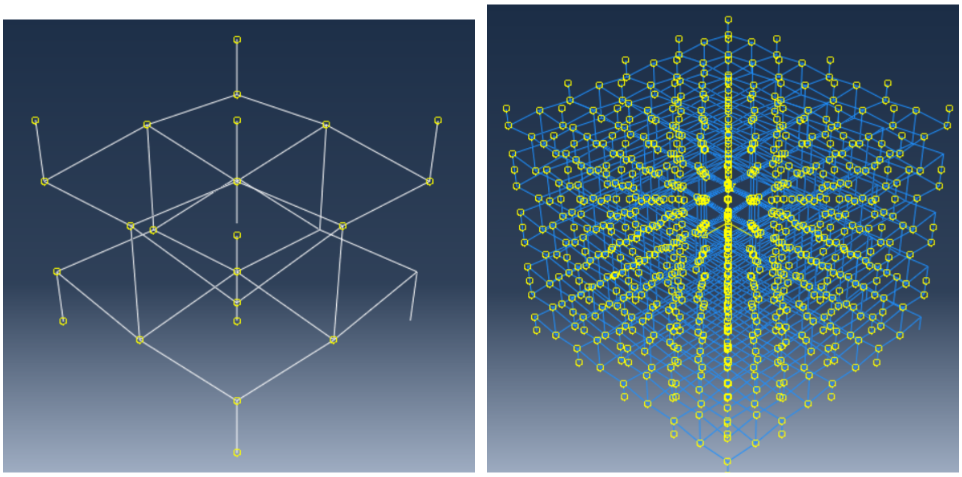
Angle 265
Radius 4.7625
Length strut 30.500
Number of unit cells X-direction 4
Number of unit cells Y-direction 4
Number of unit cells Z-direction 5
X Size 119.8
Height unit cell 109.8
Multiplication length 2

(a) Parameters **(b)** Double Pyramid **(c)** Bow-tie

Figure 3.5: Parametric design

3.5. Computational design

A finite element model (FEM) in ABAQUS is created to perform a structural analysis on the lattice. The geometry as shown in Appendix B is modelled using beam elements. Furthermore, displacement control is used to obtain the full behaviour of the lattice after reaching the peak load. The bottom nodes of the lowest struts are selected for the boundary conditions, which are fully constrained in displacement and rotation. In Figure 3.6a the geometry of the unit cell is shown, which is modelled in ABAQUS. Furthermore, the repetition of the unit cell in xyz-direction gives the full unit cell, which is shown in Figure 3.6b. The nodes are now modelled as fully rigid, which in reality are connections through welds. The weld can be modelled as a rotational spring, this could be a follow up on this feasibility study to understand the behaviour of the lattice more in depth.



(a) ABAQUS geometry unit cell **(b)** ABAQUS geometry full lattice

Figure 3.6: ABAQUS

Table 3.3: Plastic behaviour steel [29]

Yield Stress (MPa)	Strain (-)
415	0
520	0.16

Since conventional number #3 rebar is used the properties can easily be obtained. The steel auxetic lattice contains the following properties; a density of 7800 kg/m^3, a modulus of 210 GPa and a Poisson's ratio of 0.3. Furthermore, the values for the plastic behaviour depend on the steel grade, which is 60 in our case. The values are shown in Table 3.3.

The boundary conditions of the model are chosen to be in comparison in the way of the test set-up. Displacement control is used to obtain the results, since a drop of strength is expected after reaching the ultimate strength. Furthermore, the struts at the bottom side are simply supported, except for the middle node to prevent rigid motion.

Results

The results presented in this research are extracted from the ABAQUS model, which is previously described. The figures are presented in Appendix C. The results show the lattice under deformation, the Von Mises stresses, the yielding that occurs, the reaction forces and finally the rotational deformation. These are shortly discussed below:

- **Axial deformation**: In Figure C.1 the behaviour of the lattice is shown under a displacement of 100 mm. As expected, the lattice is showing auxetic behaviour and tends to laterally contract under the loading. Furthermore, because of the applied boundary conditions the struts on the bottom side tend to go outwards. As mentioned before, the middle node on the bottom side is constraint to prevent rigid body motion.
- **Von Mises stresses**: The final step of the Von Mises stresses under a 100 mm displacement is presented in Figure C.2. Be aware, these are the stresses over a surface of a strut. It should be noticed, that the stresses in the nodes are the most critical. It is therefore of high importance that the welds are correctly performed during the fabrication process.
- **Yielding**: Input of Table 3.3 is causing the yielding behaviour that is visible in Figure C.3. Since the stresses are considerably high in the nodes, the yielding is there also expected. Besides this, the yielding that occurs, increases from top to bottom since most of the struts are plastically deforming on the lower part of the lattice.
- **Reaction forces**: As a result of the applied displacement, reaction force occur on the top and

bottom struts. Since the struts on the bottom side are deforming outwards, the reaction forces for the outer ones are decreasing. On the other side, the reaction forces for the inner nodes are increasing. The results are shown in Figure C.4.

- **Rotational deformation**: Following up on the effect of the reaction force on the lower side of the lattice, the main rotational displacement is shown to be there too, see Figure C.5.

3.6. Conclusions

This chapter gives a closer look into Robotics, namely the geometric system, cooperative robotic fabrication, material system and the parametric design. The following conclusions are drawn based on this chapter;

- A geometric system must be predefined before going into fabrication, including all bar positions.
- Support structures have to be designed to ensure proper connections between the welds. Besides, the bars must be clamped to maintain their position.
- A cooperative robotic fabrication work approach contains many elements, such as: the assembly method, tolerances, pick-up procedure, robotic assignment and path planning. As a result, it is difficult to program and many elements depend on each other.
- Several protocols to use robotics that have been used by researchers are presented in Appendix A.
- Regular rebar number #3 and #4 are used for the fabrication of the upscaled lattices. Besides, conventional welding is used to create connection. The properties of the rebar and welding material are presented in this chapter.
- A short parametric design study is performed in Grasshopper for Rhinoceros 7 to model the geometry of the bow-tie and double pyramid architecture. The parameters presented in the input definition defined in section 2.3 enables making quick changes. For further research, it has shown to be a power full tool when comparing different architectures.
- A computational study is performed using ABAQUS. The general behaviour is presented in Appendix C.

4

Conclusions and Recommendations

This study is presenting a feasibility study on the upscaling of architected metamaterials for applications in civil infrastructure: auxetic lattices for confining concrete by using robotics.

Firstly, the background information and positive influence of auxetic lattices on the mechanical properties as confinement of concrete is given. Secondly, a brief literature study is performed on the current practice of robotics in construction and their contribution. Which is followed up by discussing several work approaches, parametric- and computational design methods and a multi-robotic fabrication process. Finally, the full work process for the use of robotics is discussed step by step.

The goal of the report is to define a feasibility study on the potential on the upscaling of architected lattices. Besides that, recommendations are given for further research.

4.1. Conclusions

In this part the research questions that have been stated in section 1.5 are briefly discussed and the main conclusions of this research are presented.

1. *What robotics have already been used for construction?*

The construction industry is behind on productivity when comparing it with the automobile industry. There are several reasons like: safety, productivity, performance, etc. to use robotics in construction. Furthermore, there have been multiple examples of robotics that have been used in construction. However, there has been a different focus of the construction industry in terms of R&D, this has mostly been in virtual reality, monitoring using sensor-based equipment and tracking.

2. *What protocol could be used to manufacture upscaled auxetic lattices?*

Several protocols that have been used by researchers to use robotics are presented in annex A. It is clearly visible, that each different motion has to be carefully planned. Each action, represents multiple movements either by the robot or clamp in order to be successful.

3. *What work approach is used to control robotics?*

Increasing productivity of robotics is achieved by multi-robotic fabrication. However, the complexity of fabrication increases drastically. A clear work approach should be defined. Besides this, there are many open source plug-ins for Rhinoceros 7 that help modelling the design and thereafter correctly defining the input to control the robots.

First of all, a geometric system must be predefined before going into fabrication, including all bar positions. Secondly, the support structures have to be designed to ensure proper connections between the welds. Moreover, the bars must be clamped to maintain their position. Furthermore, a cooperative robotic fabrication work approach contains many elements, such as: the assembly method, tolerances, pick-up procedure, robotic assignment and path planning. As a result, it is difficult to program with many elements depending on each other. Finally, literature is showing different work approaches to control robotics, but all seem to be able to remain stability and have a solution for the case study to succeed.

4.2. Recommendations

Furthermore, some recommendations for future research are presented below. Besides, some ideas are presented, which could help in manufacturing the full lattice of both architectures.

Structural performance
The structural performance of the lattice will be tested in one of the UMass labs. The research is focused on the state of the art behaviour of upscaled lattices. Failure mechanisms such as buckling or local fracture of the welds are possible.

Test specimen/manufacturing
It is recommended to keep the small bars on the bottom- and top part of the double pyramid lattice to remain auxetic behaviour and an experimental specimen.

Experimental study
In order to understand the behaviour of the lattice, compression tests can be performed. Under a compressive load, the auxetic behaviour should be visible and local imperfection/failures can be observed. Also stress/strain and force/displacement curves can be created.

Computational verification
In order to understand the behaviour of the lattice the mechanical properties and observations obtained from the test should be used. A finite element model software, such as ABAQUS could be used to model the lattice. Furthermore, the mechanical properties can be plugged in to the model to look for similar results as the tests. A formula, representing the behaviour of the lattice can be obtained.

Fabrication
The fabrication of the lattice is labour intensive and should be reduced with the help of robotics. However, it is recommended to first start fabrication using manual welding. There any many reasons for this, such as: setting up an fully functional algorithm is extremely complex, the design can be changed numerous times due to new insights and the process of creating a lattice can already be started. After which, the lattice can be tested in the lab for new insights.

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A

Plan skeleton

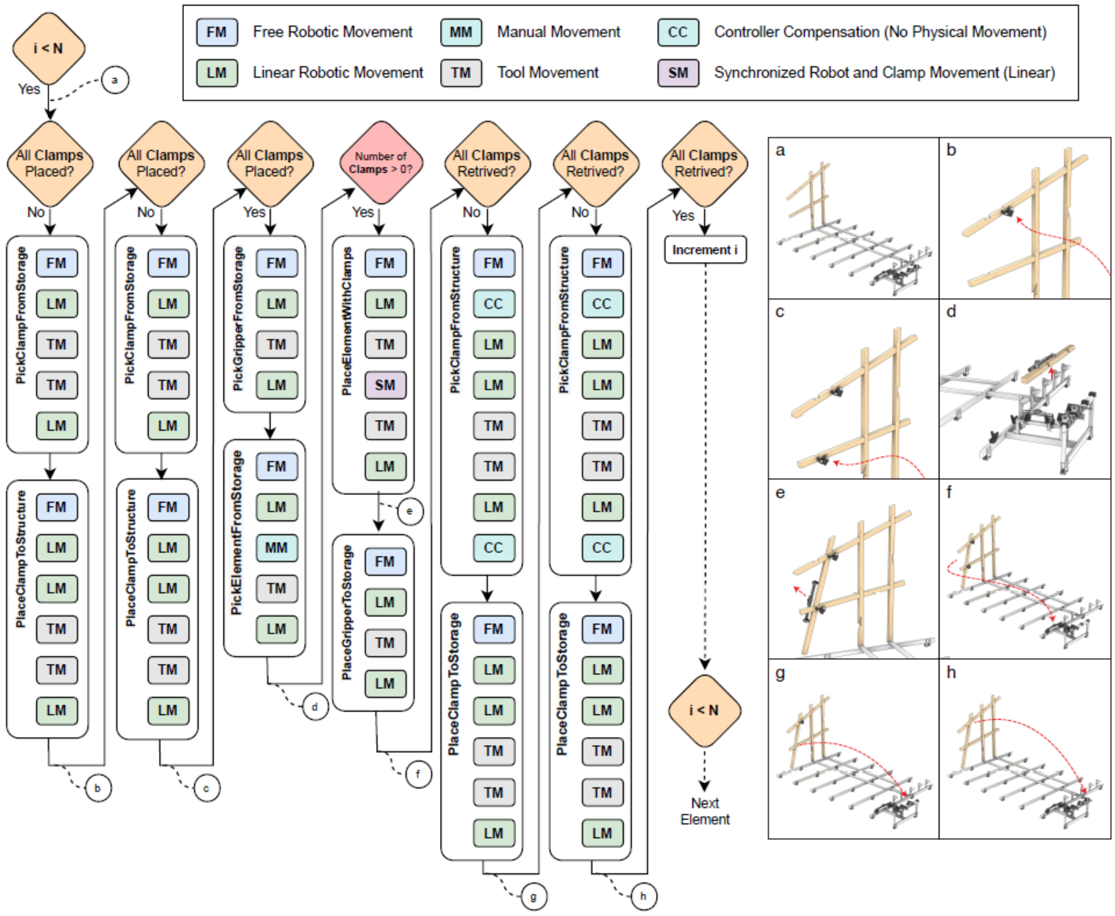


Figure A.1: Plan skeleton [14]

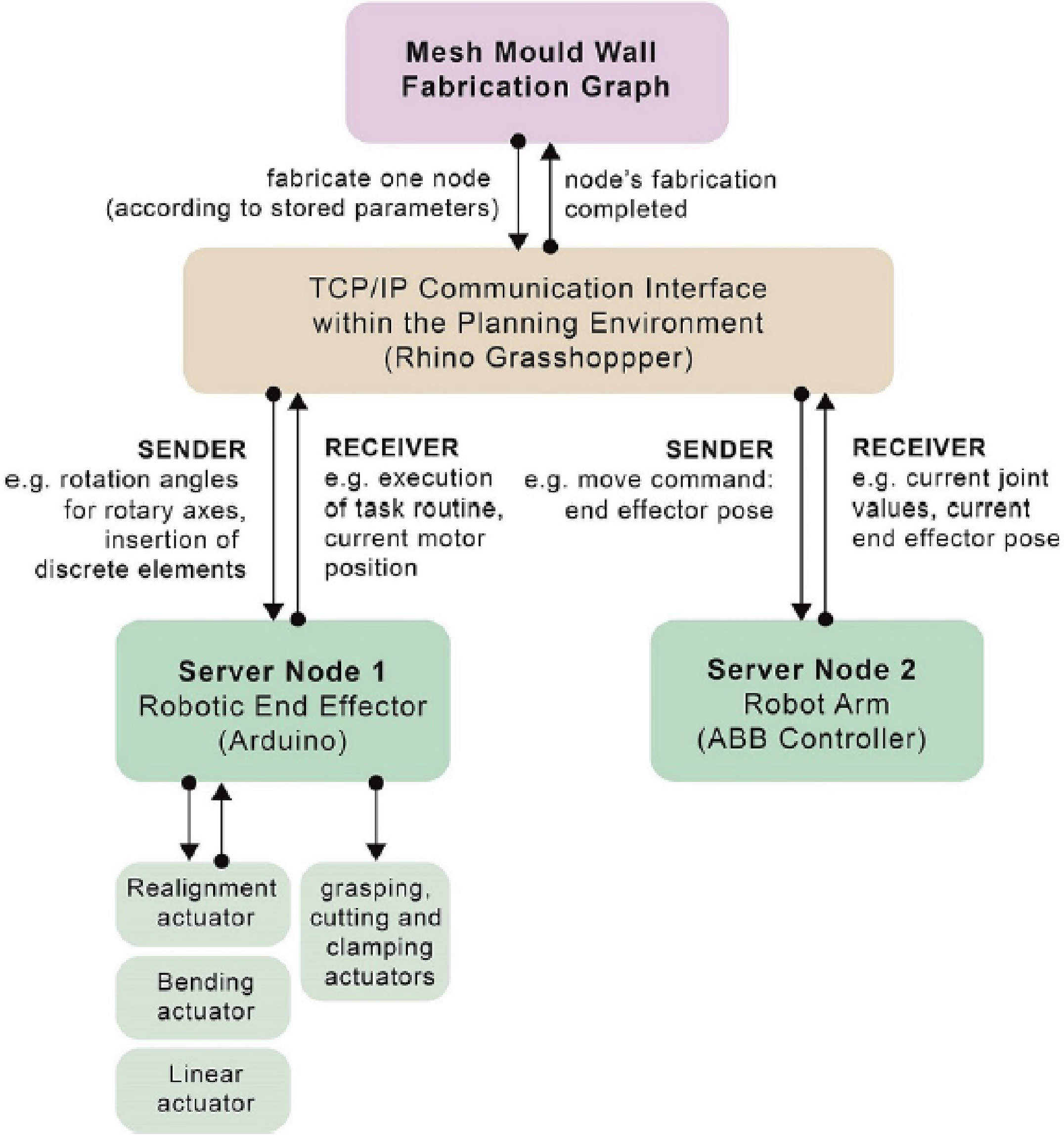
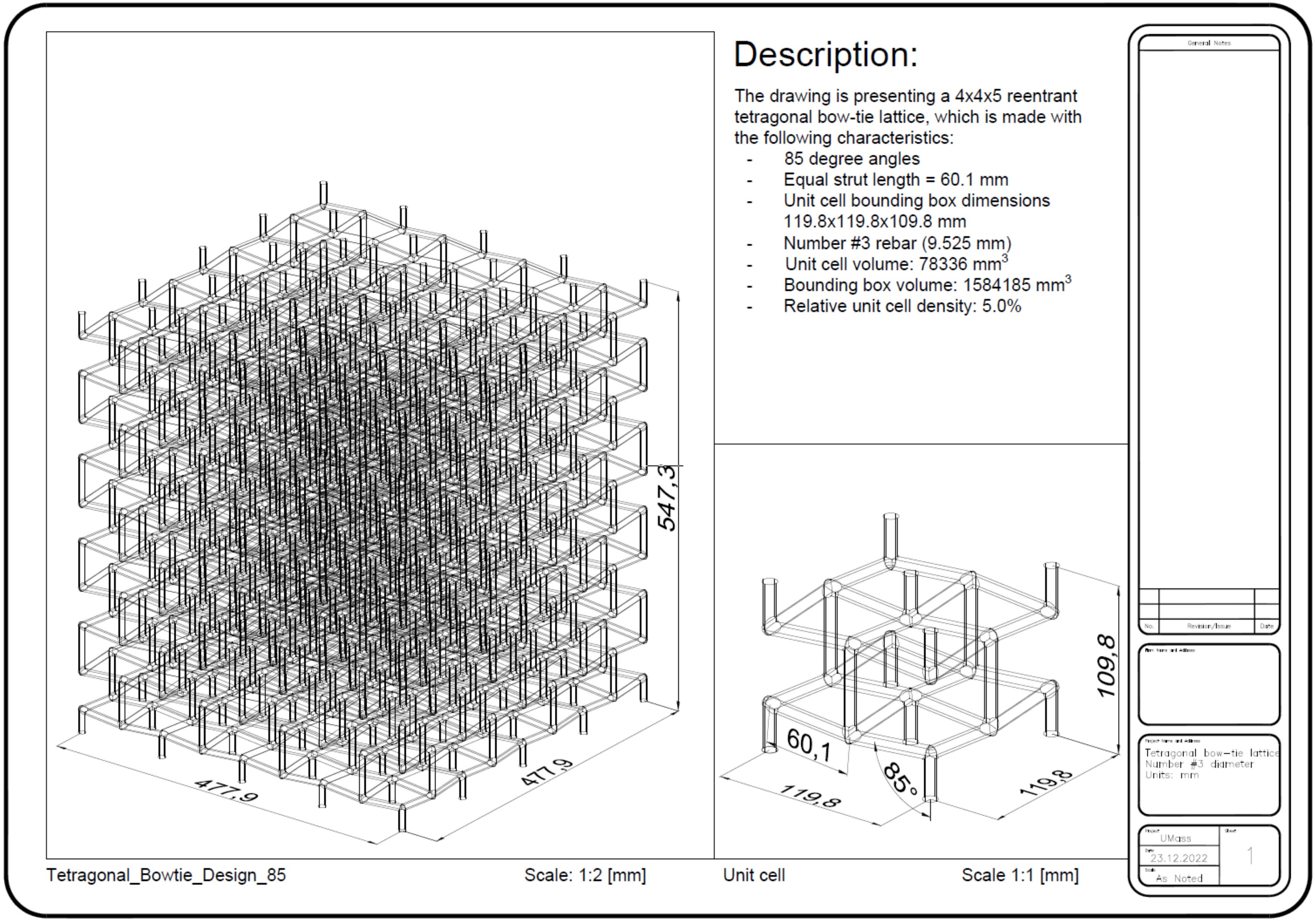


Figure A.2: Control framework/communication protocol [18]

B

Architecture lattices



Description:

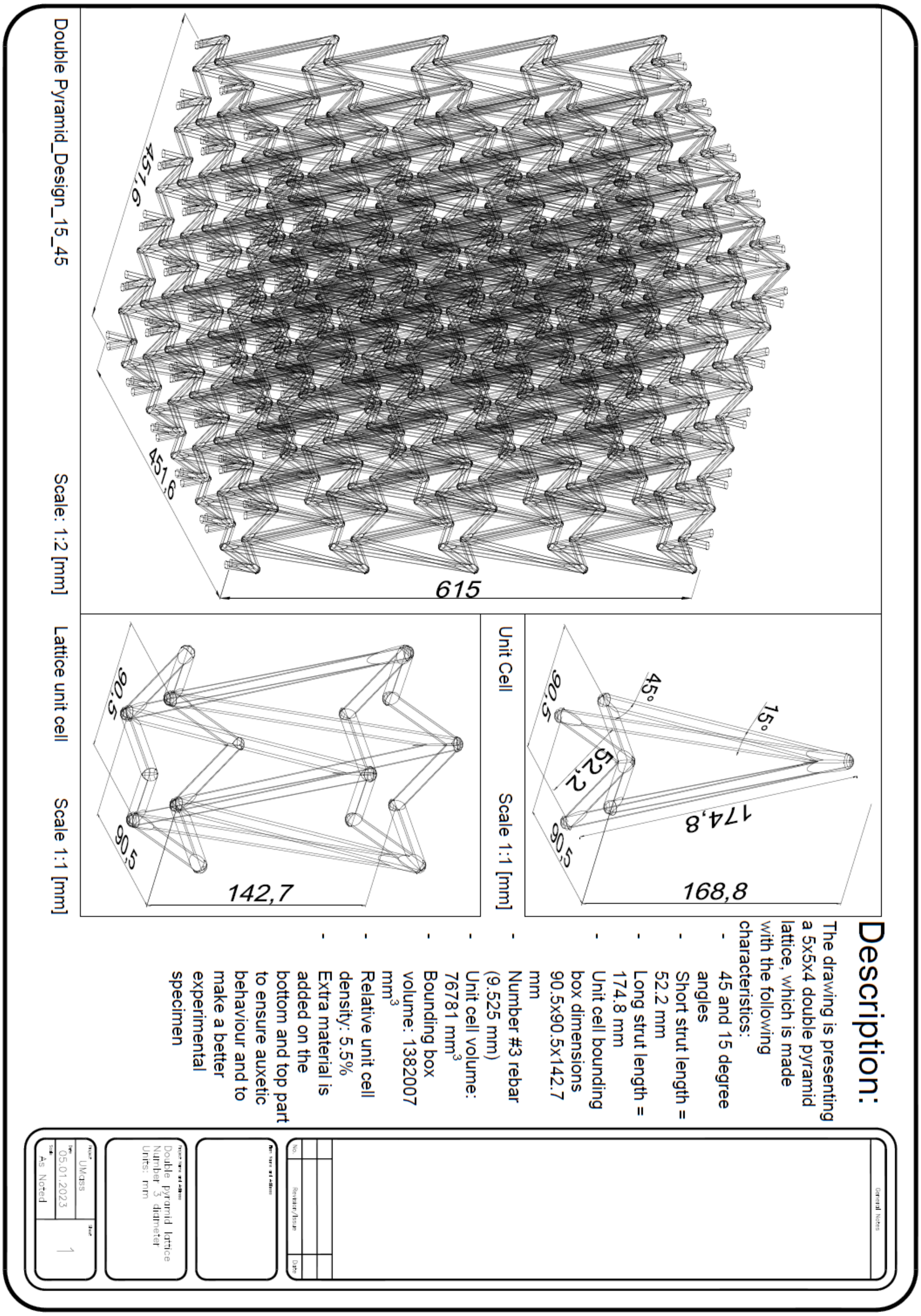
The drawing is presenting a 4x4x5 reentrant tetragonal bow-tie lattice, which is made with the following characteristics:

- 85 degree angles
- Equal strut length = 60.1 mm
- Unit cell bounding box dimensions 119.8x119.8x109.8 mm
- Number #3 rebar (9.525 mm)
- Unit cell volume: 78336 mm^3
- Bounding box volume: 1584185 mm^3
- Relative unit cell density: 5.0%

Project Name and Address
Tetragonal bow–tie lattice
Number #3 diameter
Units: mm

Project: UMass
Date: 23.12.2022
Scale: As Noted
Sheet: 1

Figure B.1: Bow-tie lattice



Description:

The drawing is presenting a 5x5x4 double pyramid lattice, which is made with the following characteristics:

- 45 and 15 degree angles
- Short strut length = 52.2 mm
- Long strut length = 174.8 mm
- Unit cell bounding box dimensions 90.5x90.5x142.7 mm
- Number #3 rebar (9.525 mm)
- Unit cell volume: 76781 mm^3
- Bounding box volume: 1382007 mm^3
- Relative unit cell density: 5.5%
- Extra material is added on the bottom and top part to ensure auxetic behaviour and to make a better experimental specimen

Figure B.2: Double pyramid lattice

C

ABAQUS Results

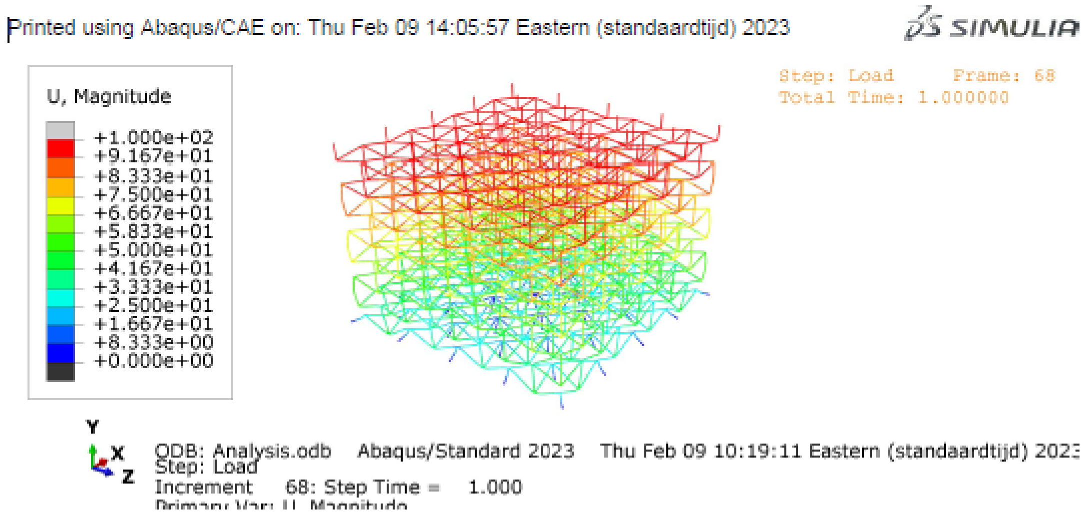


Figure C.1: Deformation

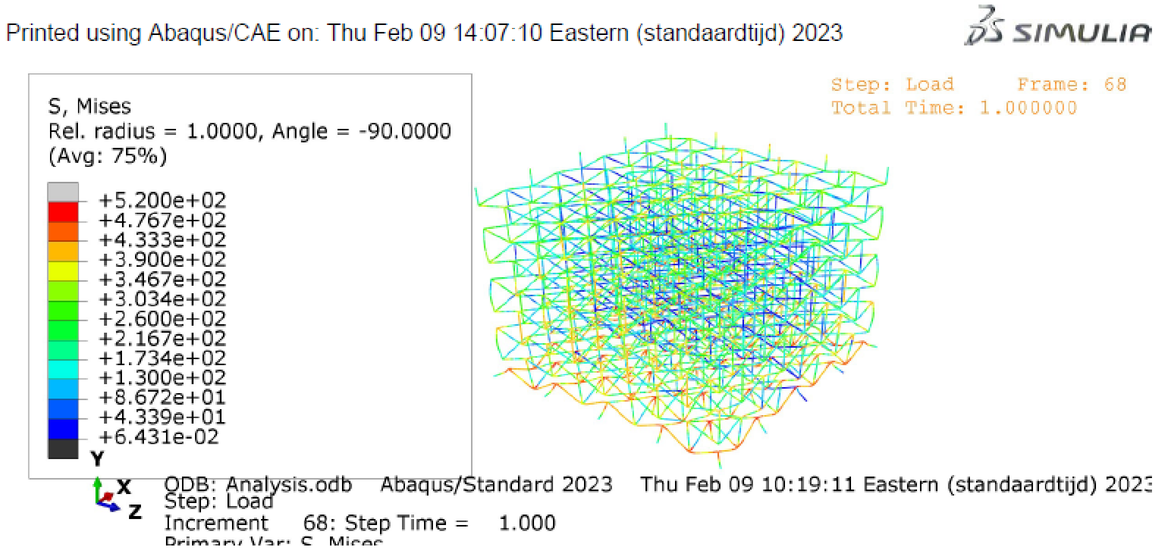


Figure C.2: Von Mises stresses

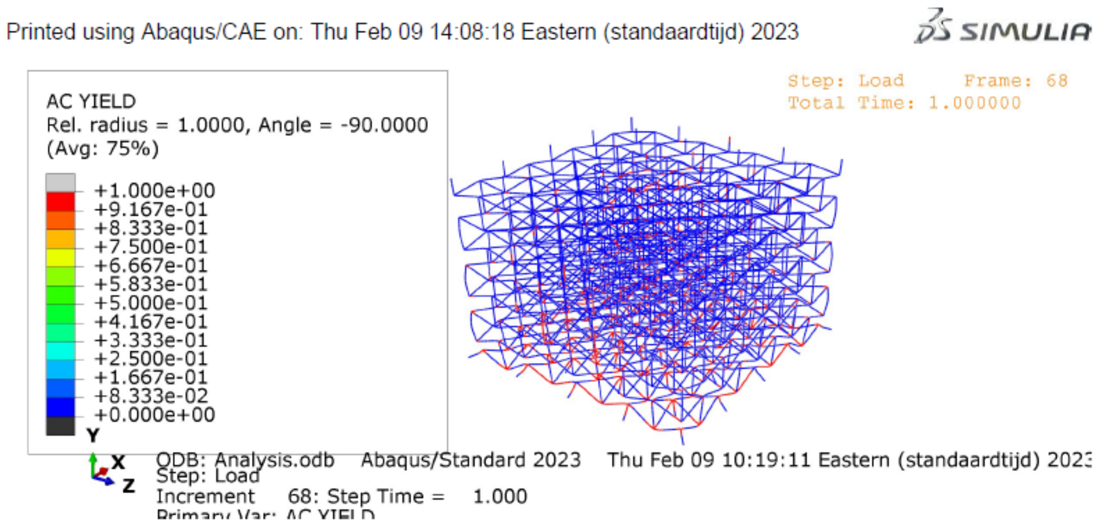


Figure C.3: Yielding of steel

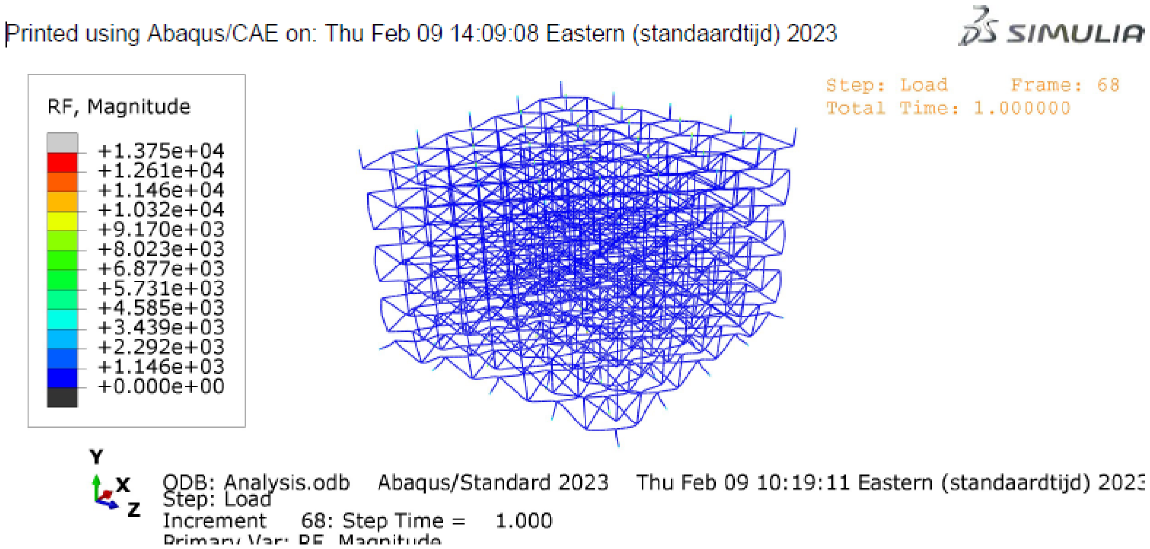


Figure C.4: Reaction forces

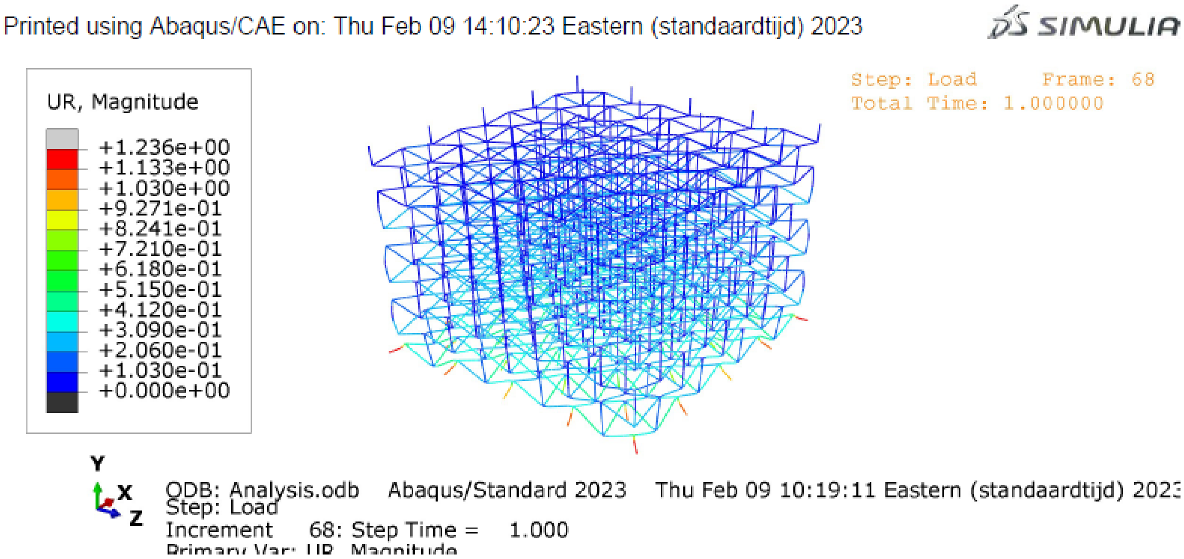


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Figure C.5: Rotational deformation