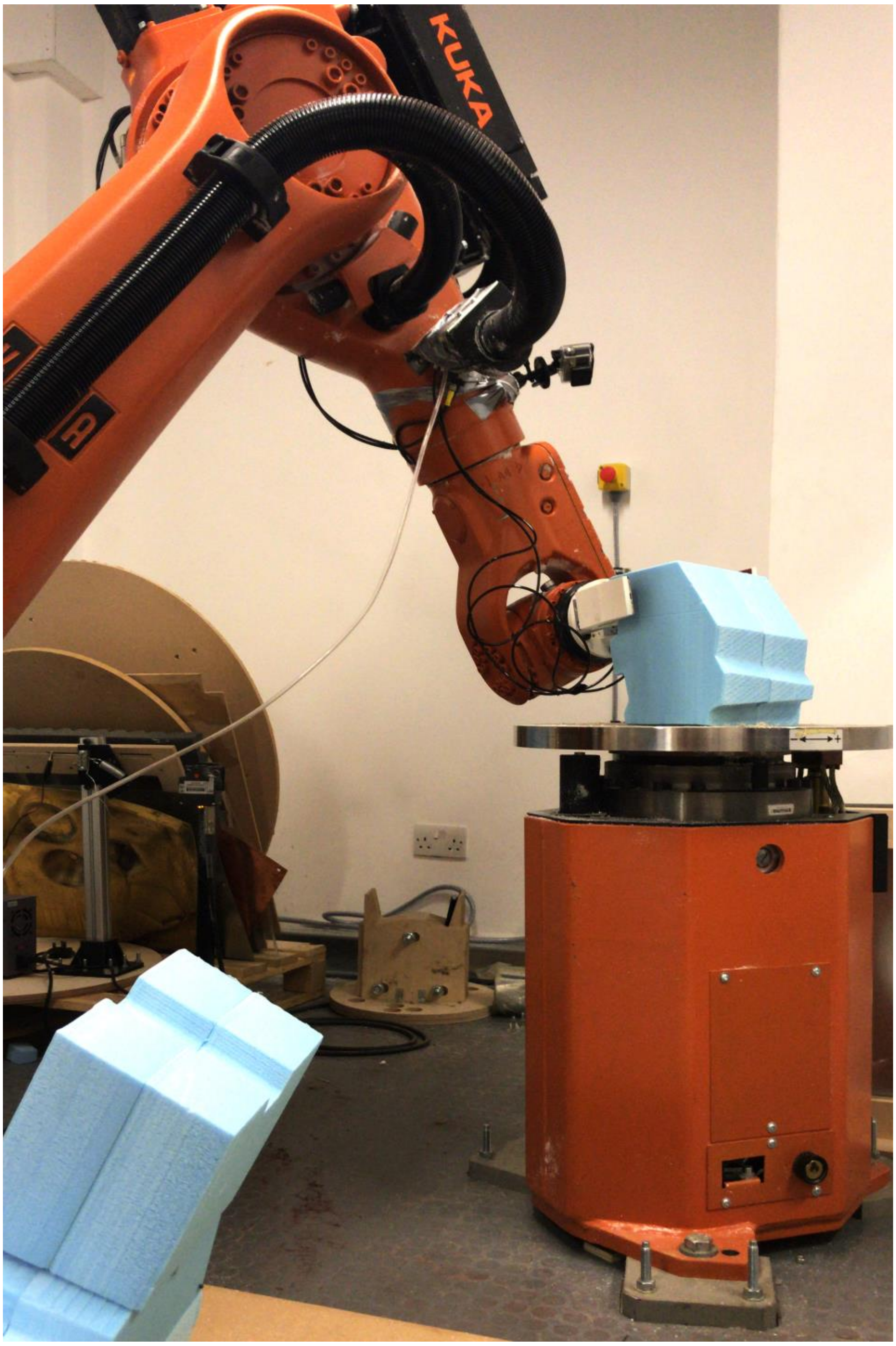
KUKA

# Towards autonomous fabrication

## Robotic assembly without scaffolding or mortar to form stable compression shells.

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**Abstract.**
Advances in robotic fabrication and computational geometry have opened up new potentials for including robotic assembly into the fabrication loop. We demonstrated a method for computing and constructing architectural geometry through the negotiation between robotic constraints and design intent constraints. A small-scale experiment structure was modelled and partially built from High Density Polyurethane foam (firm) sheets, using an industrial robotic arm in an enclosed work cell to carry out a relatively simple task of picking and placing foam panels of variable dimensions and edge angles to form a double curved structure. The complexity of this process is further increased due to the need for a scaffolding free and mortar free construction of the compression only segmented shell. This paper discussed the successes and limitations within autonomous robotic assembly as they encounter variable dimensions and angles of assembly parts and the use of friction-based interlocks to overcome design intent limitations.

**Keywords:** Friction-based interlocking, Mortar free construction, Scaffolding free construction, Robotic automation

## 1 Introduction

Shell structures are a widely used building type, which provides stable structures along with a large span. Shell structures are structurally efficient, due to the transformation of plane forces to membrane forces. However, continuous shell structures are rarely built today, due to high manufacturing costs. Segmental plate shells, composed of prefabricated planar panels, might offer an interesting alternative. Unlike single layer grid shells, which usually need bending-stiff joints to stabilize the structure, segmental plate shells could generate local bending stiffness without the help of a bending-stiff joint [1]. When three plates meet at one point and are hinged along the intersection lines, each plate is constrained by the other two; they cannot have relative movements anymore. This property helps segmental plate shells to generate a relative simple connectivity, which makes this type of structures more competitive.

The pattern of segmental plates affects the force transfer in shell structures. It defines the locations of all connections, which are the weak points in the structure. Because the material is not continuous at connections, forces will be redirected when they pass through the connections. Besides, the joint stiffness also affects the force path largely, because when the joints are stiffer, larger forces will be attracted to flow through [2]. The geometric pattern and the joint stiffness thus determine where and how the internal forces are transferred in segmental plate shells.

### 1.1 Challenges to overcome

In this project there is a heavy dependence on the use of a 6-axis robotic arm therefore leading to various negotiations between robotic constraints and design intent. The integration of multi-functional kinematic machines into creative processes allows a designer a high degree of customization enabling innovative design. Designing an efficient tool path is pivotal in Robotic Fabrication processes. This tool-path design has a direct impact on construction time, machine time and the amount of material used. It is therefore not so much a workflow that realizes a finished 3D data, rather a process that has to be implemented at early stages of design by the designer. In return, it gives the designer the ability to move past the predefined strategies of CAD-CAM (Computer Aided Design / Manufacturing). This is achieved by carefully considering and implementing the properties of tools, the machines in addition to the properties of the material in use2. Therefore, the challenges of the robotic construction are clearly outlined:

I. Scaffolding free [compression only] segmented shell fabrication
II. Mortar free construction
III. Variants in panel dimensions and edge angles

## 2 Mortar free and scaffolding-free assembly

### 2.1 Scaffolding free construction: Phasing of construction

For compression-based structures to be fabricated in most cases there is a need for temporary scaffolding to be constructed, over which the structures are built (Figure 1).

The scaffolding is giving to the unfinished shell structural stability and keeps unsecured voussoirs in place. However, it is labor-intensive, as well as time and material consuming. The mortar binding capacities play important role in the construction process due to the ability to hold together discretized shell’s voussoirs together. Nevertheless, the mortar usage increases the tolerances within the material system and frequently cause breakage due to the usage of multiple materials within the system.

Through the research made at the case studies, such as Free-form Catalan Thin-tile vault, Zurich, Switzerland and Armadillo Vault, Venice, Italy by Block Research Group and others it became clear, that the need of the formwork and mortar is essential in most of the recently developed material systems for the shell structures [3]. The need of formwork and mortar is hard to overcome while constructing shells.

**Fig. 1.** Free-form Catalan Thin-tile vault, Zurich, Switzerland. BLOCK research group. http://block.arch.ethz.ch/brg/project/free-form-catalan-thin-tile-vault

This stage proved to be a challenging aspect in this research. The proposed structure is a compression only structure and therefore, to be fabricated would generally require a temporary scaffolding. However, it was clear from the design intent the use of scaffolding would not be logical in this context and therefore had to be completely illogical in this context and therefore had to be completely ruled out. Therefore, various methods were analysed to create a freemason construction system. Phasing of the construction sequence in such a way that freemason construction could be utilised is explored further.

Due to the design intent, mortar free and scaffolding-free assembly, it becomes necessary to phase the fabrication process. This process of phasing also allows for structurally sound fabrication. The basic subdivision for the phasing of the structure is illustrated in the figure [put image], this allows for organized work flow, constructing bottom up providing intervals for the robots to assemble the successive structures as required. The tolerance seams structures are assembled in a layer by layer manner and joined after the fabrication of the unit structure it supports (Figure 2).

## 2.2 Panel Variation: Fabrication Set Up

A key aspect is to define and develop a suitable and coordinated design and fabrication set-up for the production of the hundreds of individual voussoirs that need to be processed for a single vault design. Owing to the three-dimensional shape of the separate blocks and the geometrically complex fabrication constraints, the challenge is to coordinate the design of the individual voussoirs, in accordance with the technical machine set-up. A toolpath had to be defined taking into account the complete variation in panels properties.

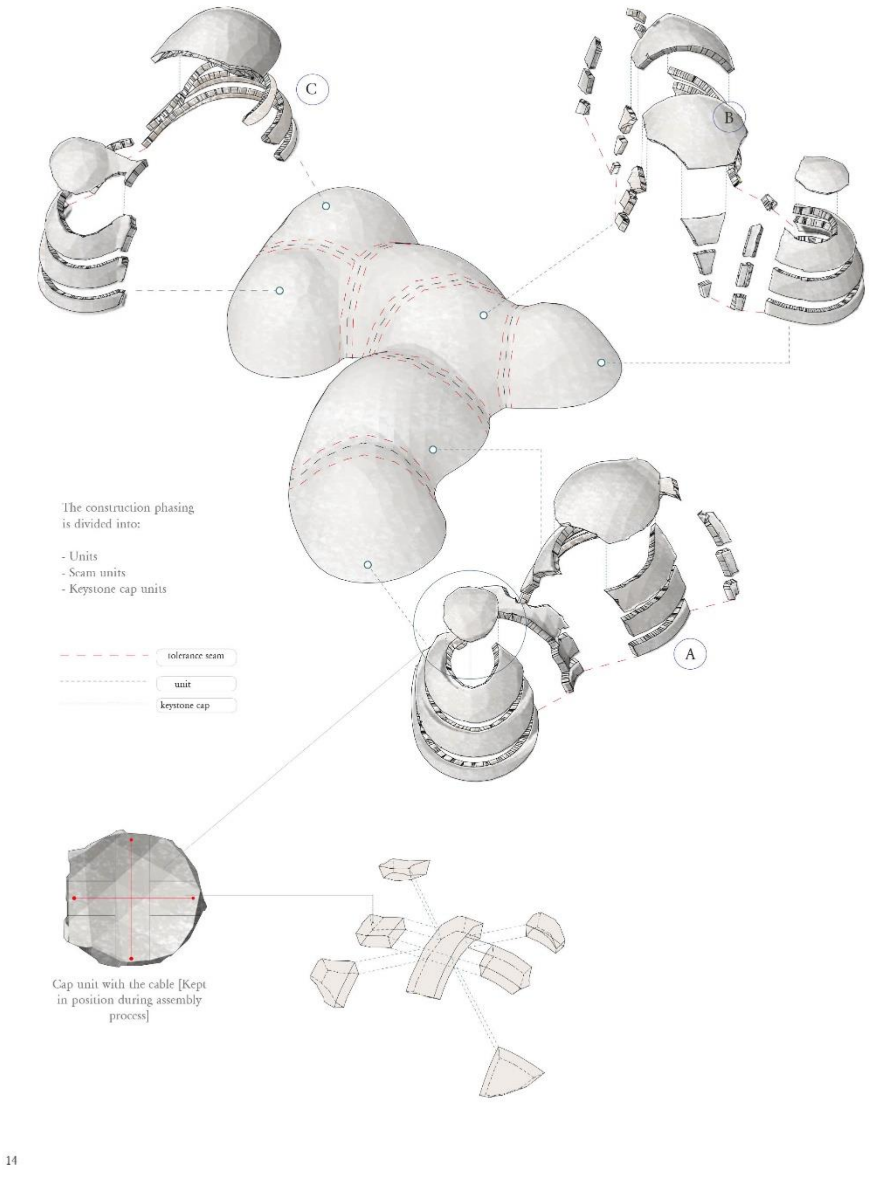

**Fig. 2.** Formwork-free and mortar-free assembly sequence

## 2.3 Mortar free construction: Structural behaviour.

The form of the vault and the geometry of the individual stone blocks is designed, such that the vault stands without any mortar, just by friction between the blocks. This is possible, because of the existence of a compression-only force pattern, generated with TNA [4]. The structural behaviour of such a shell structure is invariant to scaling, as long as the blocks have sufficient friction.

This invariance in scale allows the building of a scale model with the same structural behavior like the real vault from any not deformable modelling material (Figure 3).

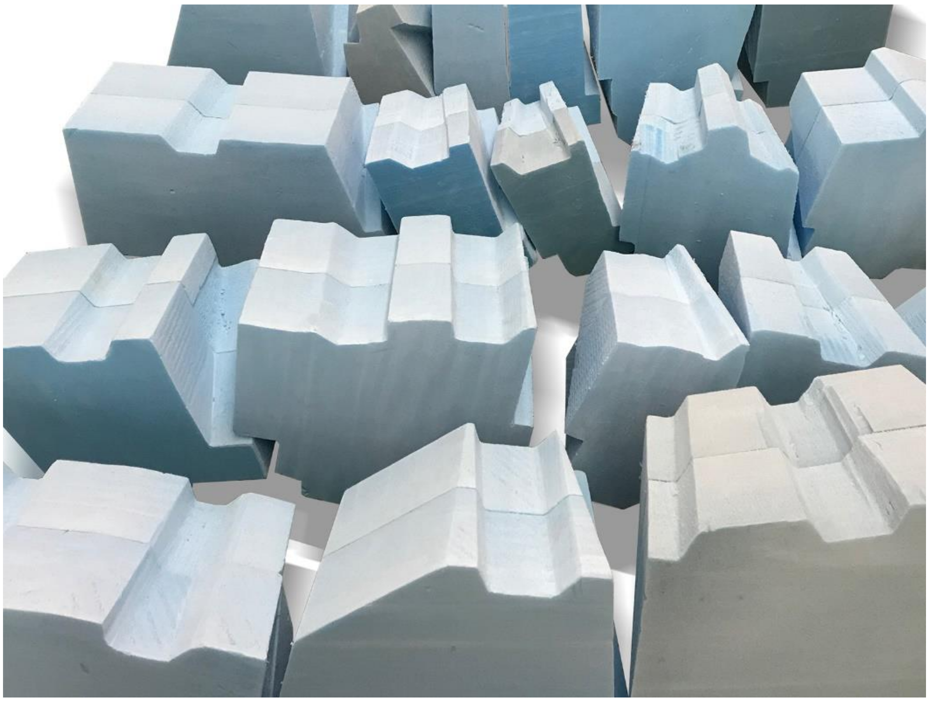

**Fig. 3.** Variation in shapes and sizes of components within one test patch.

## 2.4 Assembly Operation

Robotic pick and place automation speeds up the process of picking parts up and placing them in new and different locations, increasing production rates. With many end-of-arm-tooling options available, pick and place robots can be customized to fit specific production requirements. Moving large, small, heavy, or hard-to-handle products can be an easy task to automate in the factory line.

Consistency is also a benefit of using a pick and place system. The robots can be easily programmed and tooled to provide multiple applications if required. An increase in output with a pick and place robot system offer long-term savings to construction processes. With the advancements in technology and affordability of robots, more pick and place robotic cells are being installed for automation applications [5].

This 'pick and place' system is utilised in the proposed fabrication sequence.

## 2.5 End Effector Design and Development

Taking further this research, physical experiments were aimed to be achieved using a KUKA KR60 multi axis robotic arm. A suitable end effector [tool head] was designed and developed for physical tests.

The process of picking and placing the modules has to be automated integrating its functions into a tool head. This automation process brought in several parameters that had to be taken into consideration. The end effector had to be well designed and oriented to fit the robot arm flange.

The design of the end effector can be divided into 3 parts which fit together to perform the required task.

The 3 parts are:

I) Flange connector
II) Pneumatic gripper
III) Gripper

### I. Flange connector

. The flange connector is the unit that connects the custom designed gripper to the flange plate of the multi axis robotic arm. The flange acts as the point of connection between the robot arm and the tasks to be accomplished. The orientation of the robot is based on this connection making it pivotal to the assembly process.

### II. Pneumatic gripper

. The pneumatic gripper is the unit that connects the gripper set up to the flange plate of the multi axis robotic arm. The flange acts as the mechanical unit that carries out the commands. In the case of the pneumatic gripper, the gripping force can be infinitely adjusted up to the limit of 140 newtons on the ready-to-connect controller supplied.

### III. Gripper: Suction VS Pneumatic

. Suction gripper provides benefits in terms of adaptivity for any plane surface. However, it has limiting weight lifting capacity and requires high-density materials only. Moreover, the strength of the grip is inefficient for the large-scale blocks.

Pneumatic gripper, on the other hand, provides strong grip and easy customisation. As a drawback, it provides only one rigid closing position which should work for all the blocks of the system. A pneumatic gripper was selected for the experiments.

### 2.6 Flange design and development

The main aim of the gripper is to accommodate panels with various dimensions and grip the panel perpendicular to the planes. Since all the panels have different sizes and angles of side surfaces this becomes a challenging task. However, the two largest sides of all the panels are parallel, flat, and are located at the same distance in all the panels [due to a constant thickness]. As far as the pneumatic gripper construction requires two surfaces parallel to each other as if the surfaces are not parallel the gripper will not close properly and/or will cause a change in the gripping position [the flanges, trying to shut properly will rotate the panel and thus damage its surface]. Therefore, using the two largest flat surfaces of the panel [representing inner and outer surface of the shell] is the optimum solution.

During this process it was brought to notice that the system has two contradicting aims:

-increase the strength of the grip and

-decrease the length of the total system.

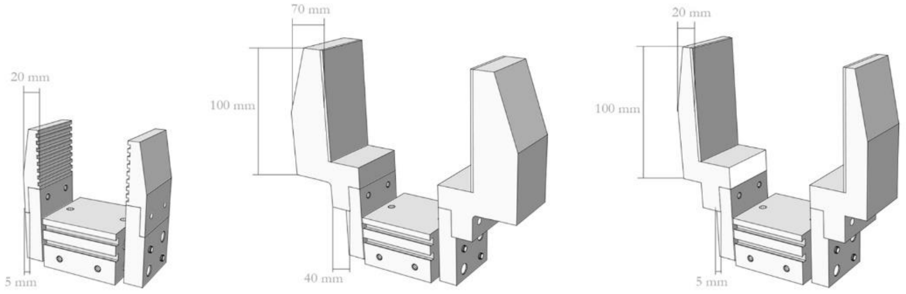

**Fig. 4.** End-effector design iterations

Extension of the 6 th axis increases the lever arm, therefore making the panels harder to lift as well as harder to manipulate in complex rotations. However minimising rotations means minimising risk of collisions and singularities. These two factors were kept in mind while designing the end effector (Figure 4).

### Iteration I

. The first iteration of the flanges designed had a length of 20 mm. However, it is found that the dimensions of this gripper are too small. The flanges aren’t long enough to grip the panels. A serrated surface is proposed in order to increase the friction between the panels [experiment material - foam] and the flanges however this attempt is unsuccessful as the edges of the serration do not provide enough surface area to grip the panels.

**Iteration II**

. In the second attempt, the gripper is designed with longer flanges [100 MM], and the gripping distance is set to 145 MM which is 5 MM less than the panel's dimension [15 MM] with the aim that the reduced dimension will help increase the friction and keep the panels in place when being picked and placed into position.

However, it is observed during tests that in the places of contact of different materials with different densities: plastic [flanges] and metal [actuator] the plastic flanges begin to crack due to excessive pressure at these points. The use of a smaller gripping dimension [145 MM] also adds to the cracking of the plastic flanges along the edge.

**Iteration III**

. In the final attempt; the gripping dimension is set at 150MM [exact dimension of panels], the plastic flanges are made thicker and 3D printer with a denser in-fill, and also the contacting surfaces of the flange are lined with a low-density sand paper [Grit 50] in order to increase friction.

During the conducted physical tests, this end effector is successful in picking and placing the panels with no alterations required. While the friction of the foam selected for physical experiments and the finished peat product is comparable [similar] for the end effector design onsite the dimensions of the flanges would have to be altered and exploration must be conducted into increasing friction between the flanges and finished peat panels.

## 3 Local Sequence

. A patch is selected from the total structure to analyse and perform physical tests to prove the ‘pick and place’ fabrication system. The toolpath followed at the local scale is a simplistic one following one direction, constructed row by row from bottom to top such that each panel is half locked by two sides and has two free sides also. However, once the successive panel is placed, the previous panel is fully locked thus creating a rigid compression only structure.

As with all robotic fabrication, the system must be clearly defined and required a onetime customisation set up before the process can then be performed continuously and accurately. The main challenges of fabrication system that are addressed at the micro scale are:

-Positioning the panels for the gripper to pick them up
-How to grip the panel securely and transfer it
-Placing the panels in required positions in the right orientation

The objective at the next stage is to place panels with variations in dimensions with accuracy, so they don’t fall during the ‘pick’ process.

The proposed automated feeder system requires guides to place the panel precisely as there is a great variation in dimensions of all the panels. However, the two largest surfaces of the panels are parallel to each other. Therefore, [on site] the feeder transfers blocks in a conveyer belt with edges that are tailored to the thickness of the panels. Therefore, the supporting guides of the panels are the side edges and the starting edge of the panel is perpendicular to the surface. However, during the experiment process the panel positions had to be precisely set up on the table.

### 3.1 Gripper relation to custom panels

However, the side of the panel to be placed on needs to be determined. This is done by calculation of the centre of gravity of each panel as well as area of each side surface. The surface with biggest area, which is not outside of the projection of centre of gravity once the panel is placed on it, is selected as a bottom surface. The gripper position adapts accordingly.

Due to the planarization of units none of the angles in the panels is 90 degrees. There is great variation within the panels with all of them measuring different sizes and different angles of the side surfaces. However, the two-main parallel largest sides of the panels are parallel, flat, and are located at the same distance in all the panels [due to equal thickness]. This is used as a benefit for the system; to utilise only one universal gripper design for all the panels.

One gripper design without the requirement to adjust flanges proves to be a simpler, more efficient and mobile [as there is no need for the end effector to be replaced during construction] design. As far as the pneumatic gripper construction requires 2 surfaces parallel to each other. If the surfaces are not parallel, the gripper will not close properly and/or will cause the change in the ‘pick’ position because the flanges while attempting to close properly will rotate the panel slightly and damage its surface or also potentially create a deviation. Therefore, using two largest flat surfaces of the panel [representing inner and outer surface of the shell] is the only appropriate method of picking the unit for construction.

In this case, the base point of the gripper [the tip that is predetermined and set up] constantly changes in order to pick up different panels. The 6th axis of the robot, therefore, is no longer parallel to the side surface, only the flanges are parallel to the panel.

**‘Pick’ position of the gripper.**

Due to the complex geometries of the voussoirs and lack of the repetitions within the morphologies, a marking system on a feeding table is proposed (Figure 5). It takes into account the closest edge point of the base surface of the voussoir as a reference point. The conjunct edge is aligned with the marked infinite line on the feeding table (in red) Therefore, every different-shaped voussoir can be easily referenced to be picked and accurately placed on the feeding table.

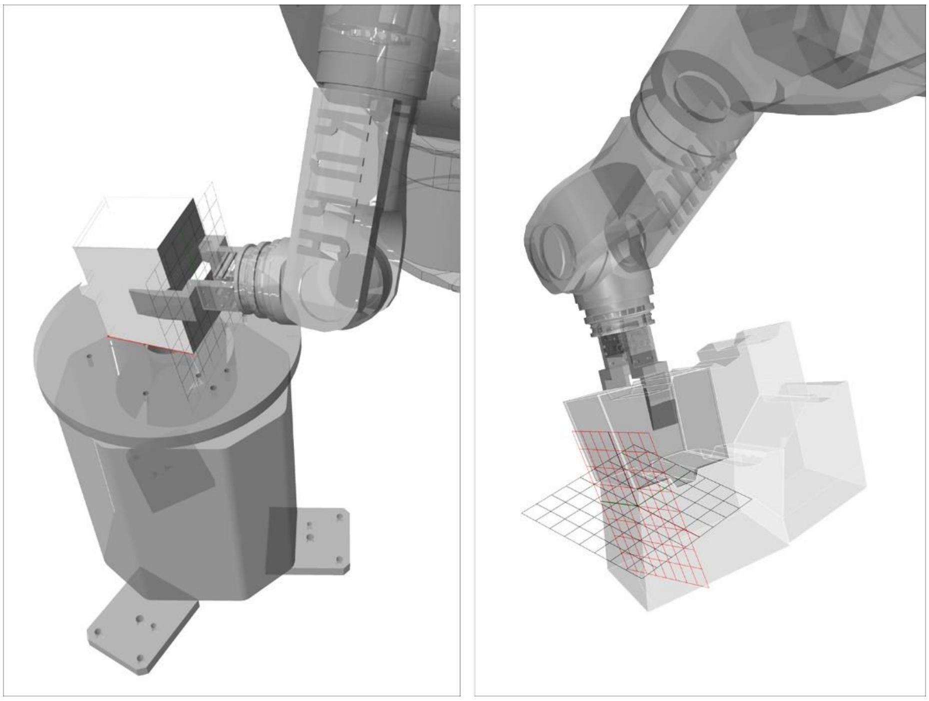

**Fig. 5.** ‘Pick’ position orientation and marking (left), ‘Place’ position orientation.

### 3.2 Robotic morphospace: Singularities avoidance.

Robotic morphospace is a domain of the movement of the robot which the tool path consists of. Not all the toolpath configuration out of the possible accessible points can be proceed by the robot. The position of the robotic arm in which the robot is facing self-collision or infinite option to move are called singularities.

Singularities avoidance is crucial for the robotic toolpath design for the interlocking systems assembly. The interlocking requires specific movement. The position of holding the block is predefined by the centre of gravity.

The 5th and 6th axis rotations are complex. For picking a block 90 degrees rotation in the 6th axis is required, while being combined with the global movement of transferring the block, it can cause self-collision. Therefore the direction of the toolpath oriented planes is important. From the experiments it was found that the axis direction should follow to outfacing. By using this method 90 degrees rotation of the 6th axis is mitigated.

## 4 Toolpath development

There are 2 types of manipulating the robot in KUKA PRC software –

- Automatically by defining the position of the end-effector tip surface or

- Manually by defining the rotation for each axis independently

The selection between methods depends on the goal which is needed to be achieved. Therefore, for the start and end position of pick and place the angles for each axis' are defined. This position is standard for all the pick and place iterations and prevents singularities. It is also used for maintaining the robot by putting additional rotations if needed. It is set in relation to the robotic morpshospace in general, possible obstacles during construction and the dimensions of the robot

The toolpath, on the other hand, requires custom, tailored to each block movement. Therefore, is the compiled of the sequence planes, where the origin defines the position of the gripper and the orientation defines the same aspect of the gripper accordingly, KUKA PRC software adjusts the position of all 6 axis in such a way, so the end-effector is positioned properly automatically.

There are several parameters which needs to be defined for the robotic algorithm:

- Start/end position – equal positions
  1st axis - pi/4
  2 nd axis pi/2
  3 rd axis - 0
  4 th axis - 0
  5 th axis -pi/2
  6 th axis - 0

-Pick Plane: it is a plane which is the starting orientation

-Safe point: additional toolpath point to prevent robot from crushing into existing constructed part of structure

-Safe Plane: safe point with specific given orientation

-Gripper positions: open/closed – commands to pneumatic gripper actuator

-Waiting time: time before/after picking/placing to ensure the accuracy of movement and panel incretion.

## 4.1 Micro scale 'Place' toolpath

This step involved contradicting criteria where minimum friction is required so that the panels can be placed perfectly into position however, for the panel to stay in position friction is required [in addition to the horizontal and vertical joinery developed] The only solution is to develop a toolpath that would allow the panels to fit perfectly into position with zero tolerance.

The main challenge in placing the panel is to avoid friction. Therefore, the direction of the movement of the panel is always parallel to the previous side panel. The 3d position of the panel, however, is derived by the panel itself due to the fact that it needs to be parallel to the gripper flange's surface.

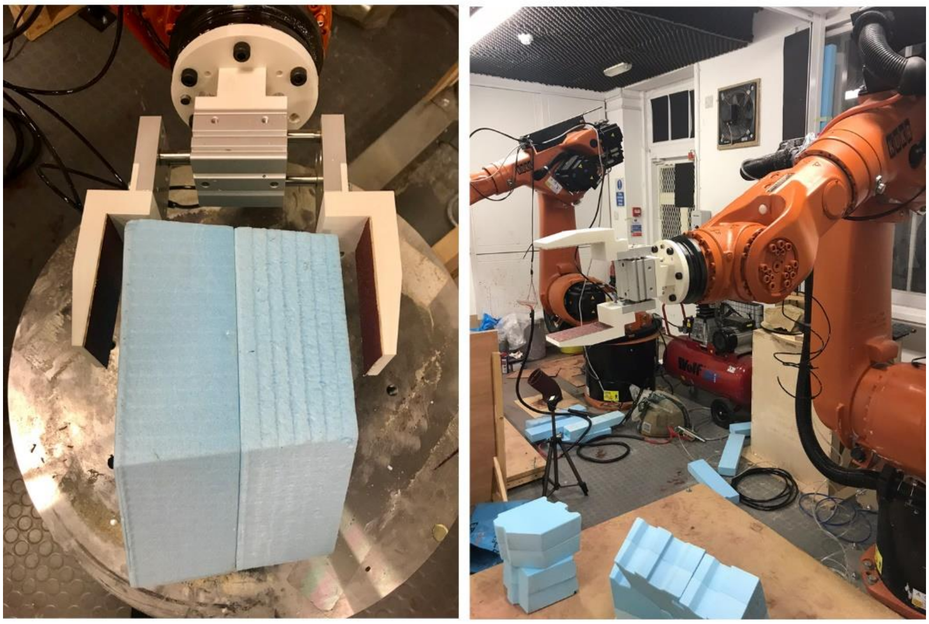

**Fig. 6.** ‘Pick’ gripper orientation (left), starting ‘0’ position of the assembly (right)

## 5 Friction based system.

By using this system different interlocking systems can be tested. Moreover, strengthen interlocking can be proposed for the particular areas of the free-form shell.

Therefore, digital mapping determines the type of interlocking for each voussoir. Geometrical relationship between local components scale and global Interlocking systems for compression only structures are based on the increase of the increase of the friction forces between the voussoirs. The interlocking holds the blocks in place if friction forces are larger. The more the increment is, the less the friction forces are and the more gravity forces are. The interlocking works within the specific threshold, which is specific for a particular structure.

A particular way of calculating this threshold is described in this section. It uses mathematical calculations of the friction forces, translated onto the geometry by using Grasshopper computation. First, the average of dimensions all the blocks within the structure is determined. Taking into consideration the interlocking components the external surface area needs to be calculated. The density of the material is an input for the gravity forces calculation. This equation is translated into the grasshopper definition. The friction and gravity forces are calculated for the each voussoir.

## 5.1 Friction forces

Friction between the panels is a key aspect of this system. Therefore, the friction forces are clearly analysed to understand its implications on the fabrication system proposed. (Figure 7)

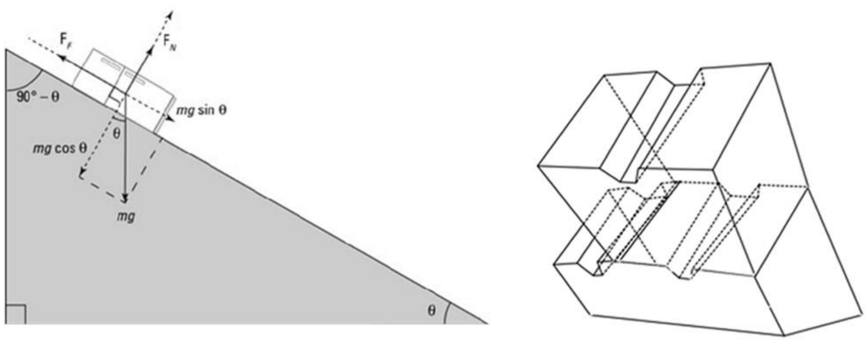

**Fig. 7.** Friction forces equilibrium (left), friction forces calculation model (right)

The friction force is the force exerted by a surface when an object moves across it - or makes an effort to move across it. The frictional force can be expressed as:

Ff = μ N
where
Ff = frictional force (N, lb)
μ = static (μs) or kinetic (μk) frictional coefficient
N = normal force (N, lb)
There are at least two types of friction forces
-Kinetic (sliding) friction force- when an object moves
-Static friction force - when an object makes an effort to move

## 5.2 Calculation of equilibrium position

In the calculations the static friction force is used as far as there is no movement in the block on the lower row. For an object pulled or pushed horizontally the normal force [N] is simply the gravity force or weight:

$$N = Fg \tag{1}$$

Fg = gravity force - or weight (N, lb)
m = mass of object (kg, slugs)
g = acceleration of gravity (9.81 m/s2)

The friction force can be modified to

$$Ff = \mu\ m\ g \tag{2}$$

The calculation is made to determine the equilibrium position with the maximum angle possible until sliding of the block.

In equilibrium all the forces are balanced. Therefore, on x axis of local block's coordinate system the forces equilibrium is:

$$m*g*\sin\theta - Ff = 0\ ,\ \text{where } Ff = \mu*m*g \tag{3}$$

On y axis of local block's coordinate system:

$$m*g*\cos\theta - Fn= 0,\ \text{where } Fn = \mu*N*\cos\theta,\ N=m*g \tag{4}$$

$$m*g*\sin\theta - \mu*m*g = m*g*\cos\theta - \mu*m*g*\cos\theta \qquad \text{/dividing by mg} \tag{5}$$

$$\sin\theta - \mu = \cos\theta - \mu\cos\theta \tag{6}$$

$$\cos2\theta\ + \sin2\theta = 1,\ \text{therefore } \cos\theta = \surd 1\text{-}\sin2\ \theta \tag{7}$$

$$\sin\theta = \cos\theta - \mu - \mu*\cos\theta \tag{8}$$

$$\sin\theta = \surd 1\text{-}\sin2\ \theta - \mu - \mu*\surd 1\text{-}\sin2\ \theta \tag{9}$$

$$\sin2\theta = 1\text{-}\ \sin2\ \theta - \mu2 -\ \mu - \mu*\sin2\ \theta \tag{10}$$

$$\sin2\theta\ *(2+\mu) = 1\text{--}\ \mu2 -\ \mu \tag{11}$$

$$\sin\theta = \surd 1\text{--}\ \mu2 -\ \mu/(2+\mu) \tag{12}$$

$$\theta = \arcsin\ \surd(1\text{--}\ \mu2 -\ \mu/(2+\mu)) \tag{13}$$

$$\theta = \arcsin\ \surd(1\text{-}0.62 - 0.6/(2+0.6)) \tag{14}$$

$$\theta = \arcsin\surd 0.41 \tag{15}$$

$$\theta = \arcsin 0.64 \tag{16}$$

$$\theta = 39.79 \tag{17}$$

Therefore, the last angle of self-supporting part of the patch without scaffolding is 90° - 39.79° = 50.21.

The section physically tested adheres to these calculations and is a section of the segmented shell that has an angle of more than 50.21°

### 5.3 Interlocking design.

The integrated interlocking system is proposed in order to resist the specific directions of collapsing (Figure 5).

The directions of voussoir collapsing are:

-Horizontal sliding towards the centre of the shell due to gravity forces

-Vertical flipping inwards once again, due to gravity forces

To prevent these two methods of the system failing a stereotomy exploration is conducted by analysing various vertical and horizontal joinery systems.

**Tapered horizontal joint**

. The horizontal interlocking tooth is tapered along the internal side of the panel to prevent the panel from sliding horizontally inwards. If there is an attempt to slide inwards, the tapered joint will prevent this movement and the panel will not be able to and will stay in position.

**Angled vertical joint**

. The vertical joint is designed in such a manner to prevent vertical flipping.

The side interlocking is redesigned in order to relate to the robotic pick and place toolpath. An angled plane is placed along the vertical sides of the panels, it is tilted against the direction of flipping.

The interlocking system is designed to fulfil two contradicting criterias –

No friction while robot is placing the voussoir in order to not damage the previously constructed part of the structure, while also maximising friction once the panel is placed to prevent movement.

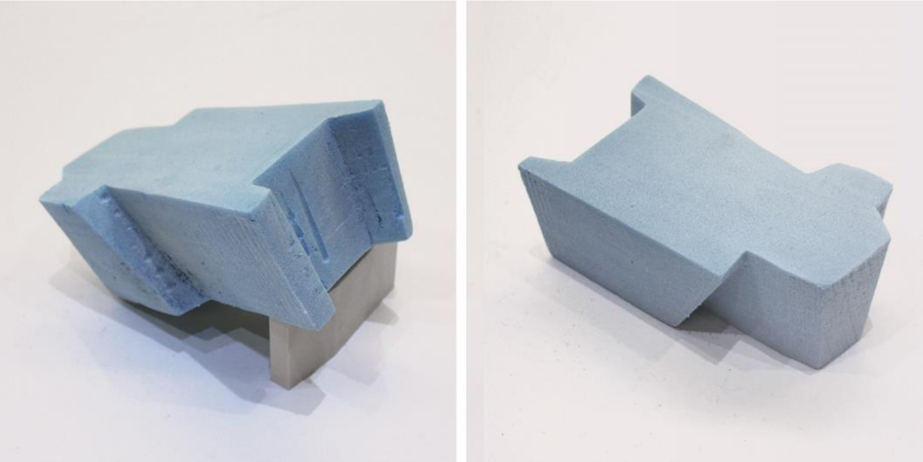

**Fig. 5.** Voussoir with the joinery system applied

### 5.4 Physical prototype

To test the proposed fabrication sequence the scaled model was designed, cut and assembled with the robot out of Styrofoam (Figure 8).

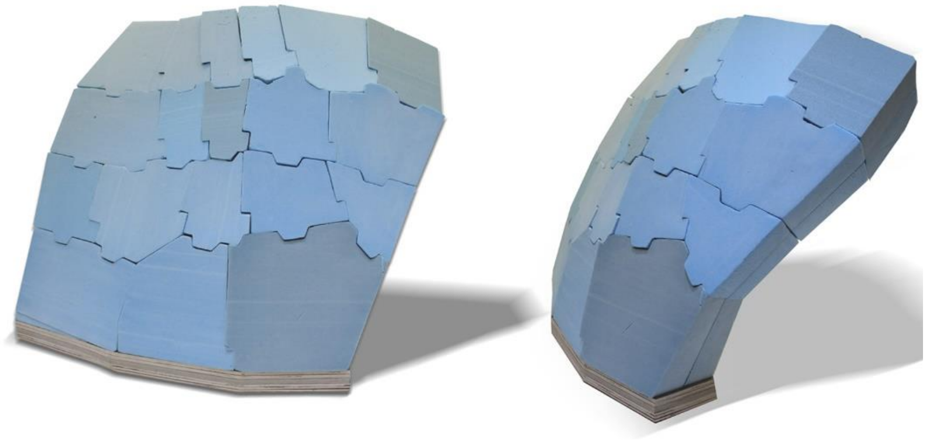

**Fig. 8.** Foam Test Patch

**Limitations.**

Because of usage of porous material the precision of the model decreased. It also brought uncertainty to the logic of the tolerance mitigation which became unused.

Due to the limitations of the CNC machine milling depth, the blocks were composed of 2 layers, CNC milled separately. The 2-layered thickness of the components dropped the precision of the CNC milling drastically and multiplied the errors caused by slight movement of the CNC blocks due to the light weight of the foam.

For the next experiments, the material – tolerance connection might be reconsidered.

## 6 Conclusion

This research investigates a novel approach to the robotic assembly of shell structures. It is aiming to create a strong relationship between geometry and assembly process and looks into the ways of integration of the robotic toolpath features within the discrete elements interlocking design. Research is conducted in parallel digitally by simulations and physically, by testing with the robot.

Overall, the research opens a broad discussion about possibilities of formwork-free and mortar-free assembly. It reveals the advantage of using robotic pick and place automation for the discrete elements structures due to precision and high speed. The challenging ambition stated was tackled by the integration of the interlocking within the geometry of the separate elements.

A future exploration needs to be done in regards to the tolerance mitigation strategy. The assembled small-scale patch can't provide sufficient information and data about the results of the tolerance mitigation strategy on an overall geometry (Section 2.1). The accuracy of the physical model decreased due to the usage of the foam as the main material. However, we do appreciate the influence of the precision of the robotic pick and assembly on the overall performance of the foam test patch.

Built up machine tolerances could potentially create a deviation in the last 'keystone' panel placed. A feedback data loop needs to be considered to address this. By integrating a feedback loop with a sensor to analyse the actual deformation, a real-time analysis regarding the last panel dimension and toolpath can be achieved.

The marking system for the 'pick' position is sensible, however, needs to be reconsidered for the large-scale assembly. It might be replaced with the conveyor or the automatic feeder. The specific KUKA robot used in this project on site might be replaced with the crane systems due to the resulting simplified vertical and horizontal movement.

Further exploration might be made in regards to the interlocking strategy. Although it does increase the overall performance and stability, it seems overcomplicated. Combined with the complexity of the voussoirs itself it creates a convoluted solution. The way to overcome this problem might be in the simplified joinery system in the areas of the structure less exposed to the high stress and additional interlocking in the weak points of the structure.

## References

1. Wendland D (2009) Experimental construction of a freeform shell structure in masonry. International Journal of Space Structures 24
2. Form Finding to Fabrication: A digital design process for masonry vaults. Lorenz Lachauer, Matthias Rippmann, Philippe Block.
3. Beyond Bending (DETAIL Special). Novel by Noelle Paulson, Philippe Block, and Tom Van Mele. 2017
4. S. Optimising Stone-Cutting Strategies for Freeform Masonry Vaults. Matthias Rippmann, John Curry, David Escobedo, Philippe Block.
5. Rethinking structural masonry: unreinforced, stone-cut shells & 1 Matthias Rippmann Dipl-Ing PhD candidate, Institute of Technology in Architecture, ETH Zurich, Switzerland & Philippe Block MSc, SMArchS, PhD
6. Construction Intelligence Center, Global Construction Outlook 2020 (Construction Intelligence Center, 2015)
7. Albu-Schäffer A, Haddadin S, Ott C, Stemmer A, Wimböck C, Hirzinger G (2007) The DLR lightweight robot: design and control concepts for robots in human