Research paper

Digital fabrication of ribbed concrete shells using automated robotic concrete spraying

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A B S T R A C T

Douby-curved ribbed concrete shells are a materially efficient means of spanning large areas such as roofs and floors. However, the fabrication of such structures poses challenges in terms of formwork manufacturing as well as material deposition. This has led to their decline compared to more prismatic shapes such as flat slabs which can be manufactured more economically. This paper presents a novel fabrication process called Automated Robotic Concrete Spraying (ARCS) by which glass fibre reinforced concrete (GFRC) is sprayed onto a curved formwork to create thin shell components of variable thickness. The trajectory planning and generation algorithm developed and implemented in ARCS to create such components is presented. Two sets of prototype shells were fabricated: one which forms the segments of a larger structural floor demonstrator and another consisting of a single component with deep ribs on a thin shell. The sequencing used to generate the spray paths for each component is outlined, with each prototype using two different strategies to add ribs onto the fabricated shells. While the fabrication process has been used in conjunction with a pin-bed mould actuating flexible formwork to create the spraying surface, the trajectory planning approach is adaptable enough such that any formwork can be utilised. Combined with the output speed of material deposition, ARCS offers the potential to enable mass production and customisation of doubly-curved ribbed structural concrete shells of variable thickness as an industrial process at an architectural scale.

1. Introduction

1.1. Literature review

Concrete shells

The versatility of concrete as a material comes from its castable nature; being able to pour the material into a mould, embed reinforcement, and allow it to set to a high compressive strength makes it unique amongst commonly used construction materials. By leveraging the fluidity of the material, designers can create highly optimised designs which lowers the overall material costs and associated carbon emissions. One such form is the thin-shell concrete structure which has been used extensively to span large distances such as roofs [1]. While the process of manufacturing the curved formwork and travelling of concrete was labour intensive, the material savings afforded by the form meant that it was still economical and practical to employ for even utilitarian structures such as factories, restaurants, and warehouses up until the 1970s [2]. Recognising the challenges of creating curved concrete shapes, engineers and architects developed methods to simplify the formwork fabrication of concrete shells: Candela utilised hyperbolic paraboloids which enabled curved surfaces to be generated from straight timber pieces for the formwork [2]; Nervi relied on precast elements which often included ribs and corrugations, connecting them on-site to create the desired shape and curvature [3]; and Neff and Bini used pneumatic formwork to inflate a flat concrete cast into the desired shape [4]. However, the global rise in labour costs eventually led to a decrease in the usage of thin-shell concrete structures due to the high cost of manufacturing complex formwork and travelling [1]; prismatic forms became heavily preferred for their construction efficiency, due to having a simple wooden formwork construction and casting process which was compatible with formwork manufacturing using flat wooden sheets [5]. This resulted in comparatively heavier and less materially efficient structures. Recently, there has been a resurgence in interest of thin-shell concrete structures, driven in part by the material saving potential of the form [1]. With the construction industry contributing an estimated 38% to all energy and process-related emissions [6] and the production of cement accounting for approximately 8% of all global carbon emissions [7], being able to lower the environmental impact of...
Concrete structures will play a crucial role in bringing the construction industry closer to global net-zero goals.

Much work has been done in evaluating the potential of thin-shell concrete structures as a materially efficient alternative to flat concrete slab flooring [8–11]. Combined with low carbon concrete mixes, thin-shell concrete forms have the potential to offer an 80% lower carbon footprint compared to traditional flooring systems [12]. However, the construction of these thin-shell concrete floors is still for the most part a manually intensive endeavour, with the concrete often cast manually onto curved timber surfaces. The inclusion of ribs – which has the potential of significantly improving structural performance – is also performed manually through the placement of material blocks made by cutting [8,10] or 3D printing [11] formers to create voids in the concrete. The extra material used for these rib formers inevitably leads to an increase in the overall embodied carbon of the structure. As such, there exists an opportunity to further reduce the carbon impact of fabricating such structures while also increasing mass-production potential and lowering the associated labour costs through automation of the construction process.

**Digital fabrication of concrete members**

Recent innovations in digital fabrication of concrete elements related to formwork technologies such as fabric formwork [13,14], cable-nets [15], pin-bed moulds [16–18], and 3D printed and milled moulds [19] as well as advances in casting methods (mainly 3D printed concrete [20–22]) offers a potential solution to the manually intensive manufacturing process of concrete shells. In addition, the flexibility afforded by custom toolpath design such as stress-based 3D printing [23,24] allows for even greater material efficiency compared to what is possible using conventional construction methods. However, while 3D printing of concrete can accurately create shapes which lend themselves to extrusion (i.e., beams, columns, and walls), curved ribbed shells are not conducive to this method, as the print direction is not easily determined and the potentially weaker bond between layers can lead to delamination [20]. In addition, embedment of reinforcement in 3D printed concrete poses additional challenges [25,26] and the relatively low output speed of most printers [20] does not lend itself to precast manufacturing plants where factory space is valuable and requires high turnover.

**Robotic concrete spraying**

Sprayed concrete (also known as shotcrete) provides an alternative means of depositing cementitious material onto a surface at high throughput. It is a widely used fabrication method in practice that comes with a tried and tested history of being employed extensively in large infrastructure projects (such as in tunnel construction) to form load bearing elements, as well as for more delicate facade elements. Several attempts have been made to couple sprayed concrete with a robotic assembly as an alternative to concrete 3D printing [27–29]. One of the advantage of sprayed concrete over 3D printed concrete is its ability to place and compact the material at the same time to construct a monolithic piece with higher layer adhesion [20]. In addition, reinforcement can easily be integrated, either within the concrete mix through chopped fibres to create glass fibre reinforced concrete (GFRC), or externally by spraying onto an existing reinforcement mesh. Much of the focus of robotic concrete spraying has been to create thin architectural elements suitable for facades [27] or gravitationally load-bearing elements which are not susceptible to cold joints and delamination, such as walls and columns [28,29]. Further investigation is required to evaluate the potential of robotic concrete spraying for fabricating curved load-bearing structural elements such as a doubly-curved ribbed concrete shell.

### 1.2. Problem statement and research objectives

The fabrication of ribbed concrete shells for structural use poses several challenges. In order to optimise material placement, a variable thickness distribution is desired. For example, less material is typically required near the apex and centre of the span compared to near the supports where large compressive stresses are present. The addition of ribs, which can significantly improve structural performance, also poses additional fabrication challenges. Lastly, a high fabrication and turn-over speed is needed to scale the fabrication process for industrial use in a precast manufacturing plant.

This research, undertaken as part of the Automating Concrete Construction project (EP/S031316/1), seeks to address these challenges through the development of a digital fabrication process called Automated Robotic Concrete Spraying (ARCS). By spraying glass fibre reinforced concrete (GFRC) onto a curved base form, variable thickness concrete shells with defined ribs can be fabricated at a high throughput. It is envisioned that the work presented will help lower the barrier to the fabrication of materially and carbon efficient concrete shell structures.

### 1.3. Contribution

This paper details a novel trajectory planning and layering approach implemented in ARCS, which was used to fabricate two sets of prototypes. As the trajectory planning and layering approach was heavily informed by the digital fabrication setup and the GFRC mix design, the latter is introduced first to better contextualise the spray path generation. Next, the algorithm developed for ARCS to generate robotic code for the fabrication of variable thickness concrete shells is detailed. Using the ARCS process, two sets of prototypes were fabricated: a nine segment shell which forms the structural floor of a 4.5 m by 4.5 m demonstrator with shallow ribs, and a ribbed shell spanning 1.5 m by 1.2 m featuring highly prominent ribs. Details regarding the fabrication of each prototype as well as an analysis of the achieved thickness distributions are presented. From the results, it can be seen that ARCS provides a means of fabricating variable thickness ribbed concrete shells at high throughput and with good accuracy.

### 2. Digital fabrication setup

The robotic assembly used to fabricate curved concrete shells was built at the National Research Facility for Infrastructure Sensing (NRFIS) laboratory at the University of Cambridge, shown in Fig. 1. It consists of an ABB IRB 6400R robotic arm with a 2.8 m reach and 200 kg maximum payload capacity, connected to an IRC5 controller, and a PS9000i GFRC spray station from Power-Sprays which was attached to the robotic arm using a custom mount. The 6 degree-of-freedom robot allows for increased flexibility in spraying position and orientation compared to a 3 degree-of-freedom gantry assembly. To form the base of the formwork, an actuated pin-bed mould (inspired by Adapa’s adaptive moulds [30]) with a lattice of carbon fibre strips was used [31]. The boundary frame was then manufactured out of phenolic plywood with fabric attached to the under side. The fabrication was performed with the shell oriented in the convex position, due to the limited reach of the robotic arm used, resulting in ribs on the intrados of the shell once rotated into its final position. A system with a larger reach such as an arm mounted on rails or a gantry would avoid this constraint. The choice of the pin-bed mould, timber frames, and fabric formwork are independent of the ARCS fabrication process; the same robotic process can easily be adapted for use with other moulds such as steel formwork or milled wax.
3 up to 75 mm with minimal slumping) without having to wait for the material can be continuously sprayed to create high mounds (tested to avoid brittle fracture of the concrete, and (3) enabling material to be sprayed in successive layers on top of each other without significant slumping. The last aspect can be leveraged to spray deep ribs, as well as changing of the concrete sprayer are difficult to automate for this laboratory setup, higher automation for this robotic setup. Regardless, some aspects of the robotic trajectory planning through intermittent pauses. In addition to the machine settings, the concrete mix must also be tuned such that a consistent slurry and fibre output are achieved. Due to the manual control, it is not feasible to alter the settings of the sprayer during the fabrication process. Various works [27,32] have tested the potential of integrating digital control of the concrete sprayer with control of the robot, which leads to a marked increase in the flexibility of the process. Integration of digital control marks the next step in enabling higher automation for this robotic setup. Regardless, some aspects of the concrete sprayer are difficult to automate for this laboratory setup, specifically the refilling of the hopper with slurry as well as changing of the fibre roving. This must be accounted for during the sequencing of the robotic trajectory planning through intermittent pauses. In addition to the machine settings, the concrete mix must also be tuned such that it is fit for pumping, aeration, and spraying.

### 2.1. Concrete sprayer

The concrete sprayer works by pumping cement slurry from a hopper to the spraying head, usually at the manufacturer recommended volumetric output of 100 cm$^3$/s. The slurry is then aerated and mixed with fibres which are chopped at the spraying head. As the mixing of the chopped fibre with the cement slurry occurs at the final step, there is the option to spray without fibres by simply stopping the air supply to the chopper motor. This can be used to create face coats—a typical process for manufacturing GFRC components, where a layer of cement slurry is sprayed without fibres to create a smooth finish which prevents the fibres from protruding out of the surface, and helps to bond the fibres within the cement matrix.

Four different settings can be tuned for the concrete sprayer: (1) the speed of the motor used to pump the slurry, (2) the air pressure used to aerate the slurry, (3) the air pressure used to run the chopper motor for the fibres, and (4) the air pressure used to push the material through the spraying head. Each of these settings are tuned beforehand and are calibrated through various tests in order to ensure that a consistent slurry and fibre output are achieved. Due to the manual control, it is not feasible to alter the settings of the sprayer during the fabrication process. Various works [27,32] have tested the potential of integrating digital control of the concrete sprayer with control of the robot, which leads to a marked increase in the flexibility of the process. Integration of digital control marks the next step in enabling higher automation for this robotic setup. Regardless, some aspects of the concrete sprayer are difficult to automate for this laboratory setup, specifically the refilling of the hopper with slurry as well as changing of the fibre roving. This must be accounted for during the sequencing of the robotic trajectory planning through intermittent pauses. In addition to the machine settings, the concrete mix must also be tuned such that it is fit for pumping, aeration, and spraying.

### 2.2. Concrete mix design

The manufacturer recommended mix design for the concrete sprayer was used to fabricate the prototype with a 5% fibre weight percentage selected. The addition of fibres helped in three aspects: (1) increasing the durability of the sprayed components, (2) providing some ductility to avoid brittle fracture of the concrete, and (3) enabling material to be sprayed in successive layers on top of each other without significant slumping. The last aspect can be leveraged to spray deep ribs, as material can be continuously sprayed to create high mounds (tested up to 75 mm with minimal slumping) without having to wait for the previous layer to set. Additives were included to allow the cement slurry to be pumped through the machine, and a high slump was achieved by tuning the water content per batch. Due to the lack of coarse aggregates, the mix was less dense than normal concrete and had a nominal density of 2000 kg/m$^3$. The mixing was performed in an alternate location and the slurry was manually transferred into the hopper of the concrete sprayer. Material quantities for a typical batch of slurry mix are listed in Table 1.

### Material testing

As the sprayed elements are meant to be load-bearing (beyond its own structural weight), it is important to characterise the material properties of the GFRC mix to determine whether there are any clear issues or barriers for employing it in structural situations. To determine the material properties of the GFRC material, 40 mm thick material test panels were sprayed across nine spraying sessions. Cracking strength and ultimate tensile strength were determined from strips cut from the sprayed panels and tested in four point bending as per BS EN 1170-5:1998 [33], while compressive strength and stiffness were determined from compression test of cubes cut from the same panel. Tests were performed at 28 days after casting and on the structural test date. A summary of the test results are shown in Table 2, showing a 28-day stiffness ($E'$) of 19 900 MPa, ultimate compressive strength ($f'c$) of 42.9 MPa, a cracking stress ($f_{ck}$) of 7.81 MPa, and an ultimate tensile strength ($f_{lt}$) of 9.43 MPa. Only a modest 20% increase in tensile strength is seen from the addition of the glass fibres in the samples. This is a result of the chopped fibres pulling out as they are unable to develop sufficient bond strength with the cement matrix—much of the increase in post-cracking strength of fibre reinforced concrete comes from the frictional bond strength between the fibre and the cement matrix.

### Table 1

| Material                | Quantity | Per batch [0.031 m$^3$] | Per m$^3$ |
|-------------------------|----------|-------------------------|-----------|
| CEM II cement           | 25 kg    | 795 kg                  |           |
| Kiln-dried sand         | 25 kg    | 795 kg                  |           |
| Water                   | 7 L      | 223 L                   |           |
| Polycure [curing agent] | 2.5 L    | 80 L                    |           |
| Flowaid [super plasticiser] | 125 mL  | 4 L                     |           |
| Pumpaid [pumping aid]   | 125 mL   | 4 L                     |           |
| AR glass fibre$^b$      | 5%       | 5%                      |           |

*Adjusted to achieve desired slump.
$^b$ Fibres chopped to 25 mm at spraying head.
matrix [34]. Increasing the fibre length may potentially help to increase bond strength, resulting in overall higher ultimate tensile strength. The addition of fibres was also found to increase the ductility of the material significantly, changing the failure mode from that of a brittle one to a ductile one.

It is expected that tuning the slurry mix to achieve a desired property will be compatible with the fabrication process as long as the required slump and viscosity is attained for pumping and spraying purposes; too viscous a mixture will result in clumping in the machine and an increase in voids in the finished product, while too fluid a mixture will result in high material slumping when sprayed onto a curved surface. It was found that a slump test value ranging from 3 to 4 rings based on BS EN 1170-1:1998 [35] was suitable; a value of 3.5 was optimal but anything within the range of 3 to 4 was still compatible with the spray trajectory planning and layering approach developed for ARCS.

3. Spray trajectory planning

In order to fabricate variable thickness curved shells, a sliced approach was taken, similar to curved-layer printing [36]. Spraying the cementitious material on a layer-by-layer basis is advantageous as it can minimise the effect of slumping and toppling during fabrication. While this can be avoided by carefully tuning the mix design of the sprayed cement slurry, tackling this through the planned spray path reduces the dependency on properly calibrated mixes.

The trajectory planning approach can be separated into two parts: (1) the generation of paths on the base surface and (2) the layering of these paths. The resulting output is a series of points, along with a normal vector, which defines a coordinate frame for the robotic end effector tool centre point (TCP), as well as the traversal speed between frames.

3.1. Spraying model

It was assumed that the material, once sprayed, deforms minimally and does not slump. The validity of this assumption depends on the mix design of the slurry. However, it was observed during testing that the inclusion of chopped fibres minimised slumping and deformations greatly as the slurry became trapped within the fibres. In addition, for concrete sprayers which are closer to conventional shotcrete machines as opposed to GFRC sprayers, the common use of accelerators results in a material which sets almost instantaneously once jetted [37,38], which agrees well with the assumption of minimal deformation and no slumping.

The parameters which affect the resulting thickness of a sprayed GFRC layer are illustrated in Fig. 2. The region sprayed from the head of the concrete sprayer can be modelled by the path projected by the spraying cone as it moves. The angle of this truncated cone is determined by the geometry of the machine’s spraying head, and was found to be 30.5° for this particular setup. In order to adjust the width of a sprayed strip (D), the distance from the target surface and the end effector (H) needs to be adjusted. This distance also affects a number of additional factors; as the distance between the spraying head and the surface reduces, there is an increase in (1) spray rebound from the concentrated air pressure, and in (2) the risk of collisions between the robotic assembly and the mould/boundary frame. The latter is avoided by performing a collision check between objects during the robotic path simulation stage using HAL Robotics Framework (see Section 4). It was found that choosing H to be between 150 mm to 300 mm provided a wide range of D between 99 mm to 181 mm, while also maintaining enough space to avoid material rebound and collisions. Further considerations must also be made for the distribution of material within the spray cone. As most of the material sprayed is concentrated in the centre of the cone, following a Gaussian-like distribution, an overlap between adjacent strips is required to achieve more even distribution on a single layer. While an analysis on the distribution of the deposited material can be performed, it was found to be highly dependent on both the machine and the settings used (specifically the air pressure used to jet the material). A simplified approach was taken where single layer specimens were sprayed with varying overlaps and one which resulted in an even layer was selected based on visual inspection. It was found that a 40% overlap between adjacent spray strips (a, with aD being the overlap distance between two adjacent strips) was suitable for fabrication. Combined with the movement speed of the spraying head (S) and the volumetric output of the slurry (Q), it is possible to calculate the average thickness of a layer (t) formed by consecutively sprayed strips using the following equation:

\[ t = (1 + 2a) \frac{Q}{SD} \]  

(1)

With a volumetric output rate of 100 cm³/s and a traversal speed of 350 mm/s (selected through testing of the machines), this results in an expected thickness per layer ranging from 2.8 mm to 5.2 mm depending on the value of H.

3.2. Generation of paths on the base surface

To spray a single curved layer, a series of paths can be generated on the base surface. These paths must be equidistant from each other in order to maintain even deposition of material. Such a family of curves can be generated based on geodesic lines; by employing geodesic lines as distance functions and generating points along set length intervals (equal to \((1 - a)D\)), a set of isolines can be generated on a surface which are equidistant from each other [39]. The slurry can then be sprayed normal to the surface along the generated isolines to deposit the material in an even manner. The approach was inspired by the generation of brick patterns on doubly-curved surfaces using geodesic...
coordinates which has similar constraints of finding equidistant paths on a curved shape [40].

The process to generate the paths on a layer is shown in Fig. 3. To start, an edge from the boundary is selected. This edge forms the first in the family of isolines and governs the direction that the geodesics are computed at (approximately perpendicular to the direction of the edge). The geodesic lines are then calculated on the base surface (in red), ensuring that they extend past the boundary. This extended surface can either be found by untrimming the NURBS surface or patching a larger surface from sampled points. Using the starting edge, a series of points can be found which consist of the closest point from each geodesic line to the aligning edge, forming the starting point for the first isoline (in green). Subsequent isolines (in blue) can be generated by traversing along the geodesic lines. Note that the first isoline need not be planar—the resulting isolines will accommodate this and will form a family of equidistant curves which ‘radiate’ from the source edge. The isolines are then trimmed to fit within the boundary and are connected together using intermediary lines. While the example shown in Fig. 3 shows no offset from the boundary, an offset can be easily implemented by initially trimming the surface by a specified distance prior to generating the isolines.

The accuracy of this approach depends on the curvature of the base surface and the number of geodesic lines used. High curvature regions force geodesic lines to curve around them, resulting in spray paths which will not be equidistant. This is illustrated in Fig. 4 which shows the maximum percentage error of the distance between isolines from the prescribed path distance \((l - a)D\) for varying numbers of geodesics used on a surface with maximum curvature of \(3 \text{ m}^{-1}\). As shown, increasing the number of geodesic lines reduces the error—at the limit, the paths will be perfectly spaced when an infinite number of geodesic lines are used. However, generating many geodesic lines increases computational load, and the resulting increase in accuracy is often not realised due to variance introduced throughout other parts of the process such as material slumping and rebound. In addition, most structural concrete shells in practice are of low curvature: Nervi’s corrugated roof for the Exhibition Palace in Turin, Italy was formed by corrugated precast elements which had a maximum curvature of \(2.63 \text{ m}^{-1}\) [3] and non-corrugated shells will typically have far lower curvatures. This means that a low number of geodesics will result in quite evenly spaced isolines for practical purposes.

### 3.3. Layering of paths

Once the base surface paths are generated, subsequent layers can be found by offsetting along the vertical direction. The normal direction was not selected as it would distort the spacing of the trajectory paths based on the curvature of the surface. However, simply offsetting will result in a constant thickness shell. To spray a variable thickness along the surface, the target region must be modified. The paths found initially on the base surface can then be trimmed to the new target region, without having to recompute a new set of paths using geodesics.

The layering process is illustrated in Fig. 5. The thickness of the shell is controlled by two surfaces: the base surface which was used to generate the base surface paths (in blue) and the top surface, which between them defines the thickness of the shell (in red). By translating the base surface vertically by the current thickness sprayed (in purple) and calculating the intersection between it and the top surface, the region where more material is required can be found. The initially generated spray path layer can then be trimmed accordingly in order to deposit material only in the modified region. Performing this consecutively until the translated base surface is fully above the top surface results in the full volume being sprayed.

Connection between subsequent layers is performed by directly traversing to the closer of the two endpoints of the next layer’s path. While this was generally found not to increase the path lengths significantly, the approach is problematic where multiple local maxima exists. In such cases, a visible ‘bridge’ between the local maxima is created. Further work can be done to better cluster layers for local maxima to avoid these trails.

While Eq. (1) can be used to calculate the thickness of each layer, its accuracy is decreased due to the inclusion of traversals between connecting paths which are not accounted for. An alternative approach would be to use the total time spent on each layer to compute the volume sprayed per layer. This can then be spread evenly along the surface in order to calculate the approximate layer thickness. Both calculations are simplified models of the real thickness of the layers; variations due to overlaps, non-uniform material distribution in a sprayed strip, and traversals on connecting paths results in a varying thickness distribution along the layer that is complex to model. It was found that assuming a uniform distribution through the second approach allowed for a practical means of computing layer thickness. Typical layer thickness was found to be around 3 mm which agrees with the values predicted by Eq. (1) using the same spraying parameters.

Once the series of paths for each layer are computed, additional paths are added to traverse between layers, and the paths are divided into a series of points which defines the spraying targets. The spray tool orientation is then determined by vertically projecting each point onto the base surface and computing the surface normal. This orientation is desirable in order to avoid spraying at an angle to the surface, which distorts the resulting spray strips as well as increases the risk of slumping down the gradient of the formwork and material rebound. Note that as each layer is found by offsetting paths vertically, the spray tool orientation for the same point offset to different layers remains the same. The boundary of the surfaces will typically require special
3.4. Process considerations

To avoid material valleys from repeating similar spray paths between layers, it is important to vary the direction that the spray paths are aligned to at each layer. As the selection of the starting edge informs the general direction of the final path, families of isolines with different orientations can be generated starting at each boundary edge. The families can then be employed on alternate layers, which results in a grid-like pattern once sprayed. The addition of an overlap between subsequent isolines (i.e., setting the path distance to be less than the width of the sprayed material) also helps to provide more even distribution.

Due to the discrete nature of the sprayed layers, more material will be sprayed than what was defined by the exterior surfaces. Thinner layers can be used if a higher fidelity is required. This can be achieved by increasing the speed of the robot’s end effector. How thin the print layers should be depends on a number of factors (i.e., thickness variation, maximum speed of robot, fibre inclusion, etc.) and should be decided upon by the designers.

The paths used to connect the trimmed isolines together, as well as those used to traverse between layers, lead to extra material accumulation which needs to be minimised. While intermittent stops of the sprayer output will be able to avoid extraneous material deposition from crossing and connecting paths [32], this was incompatible with the manual control of the concrete sprayer used in the robotic setup. Instead, in order to avoid the extra accumulation from the connecting curves, the connection traversal speed was set to be higher than the normal traversal speed, in order to minimise the time spent on undesirable paths. This can be tuned by the user and is governed by the robotic assembly’s capabilities, as well as vibrational concerns arising from potentially rapidly varying acceleration and jerk.

Lastly, as the concrete sprayer takes a few seconds to properly achieve a steady deposition of material once engaged, the sprayer should be turned on and reach a consistent output prior to traversing the planned toolpath. This can be done by traversing and pausing at a designated location outside the target area prior to spraying the planned component.

4. Implementation and workflow

The trajectory planning algorithm of ARCS was implemented in C# as a plug-in for the Grasshopper3D visual programming environment [41]. This platform is widely used in the architecture, engineering, and construction industry, and offers users a means of customising workflows. As such, designers are then free to sequence the fabrication process to whatever suits their needs. The overall workflow can be organised into three parts: the computation of spray paths and trajectories, the sequencing of paths, and the generation of robotic code. The following inputs are required to generate the spray paths and robotic code:
• Exterior NURBS surfaces defining the bottom and top layers of the shell,
• $Q$: the slurry output of the concrete spraying machine,
• $S$: the traversal speed of the end effector,
• $S'$: the traversal speed of the end effector over connecting paths or traversals from one path to another,
• $D$: the width of a spray strip which is dependent on the distance from the target sprayed surface and the end effector ($H$) and the spray cone angle, and
• $a$: percentage overlap between consecutive spray strips.

Computation of spray paths. Spray paths can be generated using two methods. The first method using geodesics to generate isolines is suitable for general shell volumes and was outlined in Section 3. This requires the bottom and top surfaces of the shell to be used as inputs to define the limits. In the second method, the paths can be obtained by polylines or curves generated through other means or defined manually. This is useful to generate patterns on the shell surface. Of particular interest is the use of graph edge traversal and Eulerisation [42] to fabricate network-like patterns which can be used to form ribs while spraying continuously (where the edges of the network forms the ribs). In either case, the output is a series of coordinate frames along with a defined trajectory speed at each segment in the global Cartesian space. For the prototypes in Section 5, the first method was used to generate the ribs on the nine segment shell, while the second method was used to generate the ribs on the ribbed shell (using principal stress lines as the rib network).

Sequencing of paths. Once generated, the various paths can be connected together. Designers have the flexibility to order and refine the process to better suit their needs and physical setup. For example, considerations for slurry loading, pauses for replacement of fibre rovings, and insertion of reinforcement can be made by creating intermittent pauses between the generated spray paths. Multiple shell specimens can also be fabricated in one program by chaining together spray paths, reducing the complexity of having to handle multiple robotic codes during the fabrication process.

Generation of robotic code. Lastly, the targets are converted into robotic code using the HAL Robotics Framework (a Grasshopper3D plug-in) which performs inverse kinematics for robotic assemblies and produces robotic machine code [43]. The plug-in can also be used in order to simulate and visualise the robotic movement in 3D to detect potential clashes, collisions, and non-compliant movements.

5. Fabrication of prototypes

Using the implemented Grasshopper plug-in, ARCS was used to fabricate two sets of prototypes with different rib dimensions: the first is a flooring system which consists of nine shell segments and the second is a deep-ribbed shell, with rib width to height ratios of 5:1 and 4:3 respectively.

5.1. Nine segment shell

The ARCS process was used to fabricate a segmented concrete shell spanning 4.5 m by 4.5 m with a thickness of 30 mm at the apex and 60 mm at the supports. ribs were also added, which created a total thickness of 60 mm along the pattern located at main compressive principal stress lines that were manually selected through principal stress analysis under dead loads. The overall shape and thicknesses were determined through a form-finding process [44]. The principal stress lines were also used to inform the segmentation of the shell, resulting in nine separate segments consisting of three unique shapes. In order to connect the segments together, shear keys were added at the interfaces to aid during construction while also minimising the risk of out-of-plane slip. The thrust of the vault was resolved using external tension ties with ends bolted to the column as opposed to the concrete, which also facilitates deconstruction and disassembly of the structure compared to embedded reinforcement.

The size of the individual segments was limited by the size of the pin-bed mould, the largest segment being the central keystone with an overall size of 1.8 m by 1.8 m. As there were only three unique shapes, only three unique frames and robotic codes were needed.

5.1.1. Spray path trajectory and sequencing

Through experimentation and testing, it was found that the following sequence provides a reliable fabrication process for the concrete segments, also illustrated in Fig. 6 with matching numbering for each stage:

1. Coat the bottom of the formwork with the slurry without fibres. This face coat prevents any fibres from protruding at the exterior of the shell and helps bond the fibres within the cement matrix.
2. Spray the internal layers with fibre. This consists of two separate paths: a boundary loop to spray the edges and an inner spray path generated using geodesic lines and isolines trimmed at an offset from the boundary. The separate treatment of the boundary was important as the frame included special features to form the shear keys and corresponds to the weaker part of the segmented shell system. Without the boundary loops, the resulting edges were found to exhibit ‘honeycombing’ effects, as the fibre blocked the slurry from filling the intricate corners formed by the shear key frame features. Treating the boundary separately compared to the inner region comes at the cost of making the
boundary a constant thickness, as the boundary spray path forms consecutive loops as opposed to layers. However, this was found to be an acceptable compromise to achieve well fabricated inter-
face edges, which were expected to be structural weak points in the assembled nine segment shell. The majority of the spraying process is spent in this stage.

3. Spray ribs by layering additional shell volumes on top of the base shell. This was found to be a suitable approach as the ribs were wide compared to their height and had variable thickness (once the base surface thickness was subtracted). Where the ribs overlap with each other (as is the case with the central segment shown in Fig. 7(a)), the speed over the overlapping region was set to be twice the base traversal speed to avoid depositing twice the required amount of material.

4. Manual corrections and modifications are performed. At this stage, the end effector was moved outside the spraying area and the concrete sprayer halted. Corrections and modifications can then be performed on the fabricated piece. This included the embedment of features such as penetrations for lifting hooks and anchors. The boundary between the sprayed material and the frame can also be refined—a process which can be necessary due to deviations from the design arising from the accuracy of the timber frame and the position of the frame with respect to the robot. This led to a significant increase in the robustness of the process: a fabricated piece can be modified and salvaged if problems occur during fabrication, avoiding the need to discard it.

5. Coat the top surface of the piece with the slurry without fibres, as was done with the bottom of the formwork.

Several additions to the robotic code were included to accommodate the specific physical setup. This includes intermittent stops at an excess material waste container, which allows for refilling of the concrete spraying hopper and resolution of any issues related to the equipment (e.g., pressurisation of air tank supply, changing of fibre roving, etc.). The parameters used to generate the spray paths are listed in Table 3. Note that the measured slurry output varies between each segment (from 11.8 kg/min to 12.6 kg/min, equivalent to a 6.5% variation). The variance is due to the manual calibration of the motor required to change the output of the slurry. This will undoubtedly affect the resulting accuracy of the produced segments as the slurry output used to generate the robotic code was set to a constant 12 kg/min.

### 5.1. Fabrication

Fabrication of the nine segment shell took place over the course of five weeks, with two segments fabricated per week with allowances for fabricating a test piece. The main limitation was the size and number of pin-beds that were available to be cast on—the fabrication process could be easily scaled up with multiple moulds to allow fabrication in parallel as opposed to in series. With three workers, the entire process from the preparation of the slurry mix, testing of the robotic assembly, spraying of the form, as well as clean up of the facility took 4 h. However, the time spent spraying was less than 30 min for each segment. Once cast, each segment was left to cure overnight before being demoulded the next day. This high turn over is a result of the high volumetric output of 100 cm$^3$/s which is advantageous for mass production and avoids cold joints compared to conventional concrete 3D printing approaches [20].

Several issues were encountered during the fabrication of the first set of segments, including the mix setting too quickly in the concrete sprayer, issues in maintaining the pressurised air supply, as well as clogging of the chopped fibres in the spraying head. However, they were readily dealt with during the fabrication process, as intermediary pauses were included in the spray path sequence, providing sufficient time to address the various issues as they occur. The majority of issues were resolved over the course of the five-week fabrication period, as different parameters were tuned and the laboratory work flow (including calibration of the robot as well as mixing and transporting of the concrete) were improved.

The nine segment shell was assembled at the NRFS laboratory at the University of Cambridge, shown in Fig. 7. Due to issues with tolerances of the timber frame resulting in approximately 10 mm deviations at each segment (amounting to an error of around 0.5%), the segments did not fit flush with each other. Using a more rigid material such as steel would make for a more accurate mould and would lend itself to reusability and offsite fabrication. Manual modifications on each segment were performed once demoulded in order to allow them to fit together for assembly.

### 5.2. Ribbed shell

In order to evaluate the potential of robotic concrete spraying in fabricating deep ribs, a thin shell specimen measuring 1.5 m by 1.2 m with highly prominent ribs was fabricated. This prototype is reminiscent of deep ribbed concrete floors by Nervi [45] and Hecker [46] which have ribs aligned along principal stress lines. Whereas the voids in those floors were created by formers, this prototype sprays the ribs without any supports, thereby reducing the total amount of formwork needed. The selected thicknesses were 15 mm for the shell and 75 mm for the thick ribs, with a width of 100 mm. The ribs were placed according to the principal stress lines of the shell under self-weight, as well as at the boundary in order to reinforce the edges, and arranged in a

| Parameter | Value |
|-----------|-------|
| **Spraying parameters** | |
| Distance between end effector and target surface (H) | 225 mm |
| Spray strip width (D) | 140 mm |
| Path overlap (e) | 40% |
| Distance between adjacent spray paths (2(1 − α)D) | 84 mm |
| Inner region offset | 35 mm |
| Additional angle incline at boundary (α) | 15° |
| Traversal speed (L) | 350 mm/s |
| Traversal speed - connections (L′) | 700 mm/s |
| Expected slurry output (Q) | 12.0 kg/min |
| Measured slurry output (Q(measured)) | 11.8 to 12.6 kg/min |

| Component details | |
| Number of components | 9 |
| Spraying time - per component | 12 to 28 min |
| Spraying time - total | 184 min |
| Sprayed volume - per component | 0.069 to 0.166 m$^3$ |
| Sprayed volume - total | 1.08 m$^3$ |

*Chosen to be 25% of spray strip width.*
denser network compared to the nine segment shell. As the ribs form the main structural system of the shell, fibres were excluded from the base shell in order to reduce the total amount of fibres, and thus the overall embodied carbon, in the component.

5.2.1. Spray path trajectory and sequencing

The trajectory path algorithm, along with the layering process used for the nine segment shell, was deemed inappropriate for the ribs of this shell as the ribs were of constant height, had a width within the range of a single spray strip width, and had a clear trajectory which should be followed to form them (i.e., along the centrelines of each rib). As such, two different approaches to generating the trajectories were combined: the trajectory of the base shell was computed using isolines of the geodesics and the trajectory of the ribs was computed from the path found through Eulerisation and graph traversal of the rib network to ensure each edge (representing a rib) was traversed at least once. As the rib network was not Eulerian, some ribs needed to be passed through multiple times in order to traverse all the ribs. Additionally, intersections between ribs have double the originally intended height as the sprayer traverses these nodes multiple times per layer. Although this was observed in the initial design stage and was intentionally included to locally strengthen the nodes, this could be easily avoided by increasing the movement speed of the sprayer at node locations. This rib spray path was then layered to attain the desired rib height.

The parameters used to generate the spray path are listed in Table 3 and the following sequence was used to fabricate the ribbed shell, also illustrated in Fig. 8 with matching numbering for each stage. Compared to the sequence used for the nine segment shell, the key differences are the exclusion of spraying inner layers (as the thin shell consists of only the face coatings) and the generation of the rib paths through graph traversal as opposed to through layering of geodesic isolines. Similar to the nine segment shell, the measured slurry output deviated from the 12 kg/min used to generate the robotic code, which was expected to result in an overall increase in the thickness of the produced shell.

1. Coat the bottom of the formwork with the slurry without fibres, forming half the thickness of the base shell.
2. Spray the ribs with fibre. This was done by stacking the path found through Eulerisation and graph network traversal ensuring each rib was sprayed at minimum once per layer.
3. Manual corrections and modifications are performed.
4. Coat the top surface of the shell with slurry without fibres, forming the remaining thickness of the base shell.

5.2.2. Fabrication

Fabrication of the ribbed shell (shown in Fig. 9) took approximately 28 min and the component was left to cure overnight before demoulding. During the fabrication of the ribbed shell, several challenges were encountered. Firstly, as the ribs at the boundary were not offset from the edges, the resulting accumulated material was almost twice the height of what was accounted for, due to the walls of the timber frame pushing material inwards from regions outside the frame. Secondly, the spray path of the ribs found from graph traversal resulted in some ribs being traversed multiple times per layer. This can be easily mitigated in the future by performing graph traversal over all layers such that each edge of the network is traversed \( n \) number of times at least, where \( n \) is the number of layers forming the rib. By doing so, the redundant paths needed to transform the network into an Eulerian graph are spread out over multiple ribs, as opposed to concentrated on one set of ribs. The extra material accumulated at the boundary as well as at the ribs passed over multiple times per layer were manually removed during the correction stage prior to the coating of the top surface.

The cured and demoulded ribbed shell is shown in Fig. 10(a). As this prototype was fabricated after the nine segment shell, the process was much better understood and refined, resulting in smoother production and fewer errors. Compared to the ribs from the nine segment shell, the ribs in this shell are much more clearly defined due to their additional height. This is highlighted clearly when viewing slices of the thickness of the shell at various locations, shown in Fig. 10(b).

6. Results and discussion

6.1. Nine segment shell

A 3D scan of the assembled nine segment shell taken using an Artec3D Leo handheld scanner is shown in Fig. 11 alongside the designed and sliced thickness distributions. The thickness shown was computed from the smallest distance between the extrados and intrados scanned surfaces at sample points, which is approximately equal to the thickness in the normal direction of the middle surface. From this data, the deviation from the sliced thickness distribution to what was achieved was determined and plotted, normalised by the maximum design thickness of 60 mm (Fig. 12). Overall, the desired thickness of each segment was achieved by the fabrication process, with the normalised deviation having a mean of 0.195 and a standard deviation of 0.202. The large deviations from the intended thickness are mainly concentrated around the boundary regions of each segment, clearly
visible in the central segment shown in Fig. 7(a) and in the thickness distribution in Fig. 11. This was caused by the separate treatment of the boundary compared to the inner region of each segment, which was deemed necessary to create a robust shear key interface between two adjacent segments. Other regions with increased thickness compared to the intended thickness include the ribs and the four corners of the assembled shell. These areas correlate to regions where many connecting paths were located, resulting in increased material deposition. In contrast, the base shell area has minimal connecting paths and achieved a thickness much closer to what was expected. Increasing the connection traversal speed is expected to improve this and bring the fabricated thickness distribution closer to what was intended. The
effects of spraying on a carbon strip lattice can also be seen to result in a smooth grid-like pattern variation throughout the entire shell which does not significantly affect the overall quality and accuracy of the segments produced.

Variations between identical segments can also be seen, most clearly with the bottom right and bottom left corner segments in Fig. 12. A major source is the manual calibration of the concrete sprayer settings as well as mix design for each segment. While a uniform mix was targeted, the desired viscosity varied between each mix and the slurry output (shown in Table 3) deviated from the 12 kg/min used to generate the spray paths. In addition, issues with the pressurised air supply used meant that the rate of fibre and slurry output varied while spraying a single segment. This was addressed in later segments by pausing and restarting the pressurised air supply throughout the fabrication process—one of various refinements adopted into the process as each segment was manufactured. These issues are not expected to be commonplace in an offsite mass production facility tailored for manufacturing of such components.

6.2. Ribbed shell

The thickness distribution of the ribbed shell obtained from a 3D scan of the fabricated piece is shown in Fig. 13 and the deviation between the designed geometry and the final scanned geometry (normalised by the designed rib thickness of 75 mm) is shown in Fig. 14. It can be seen that the intended thicknesses were generally achieved, with the normalised deviation having a mean of 0.0224 and a standard deviation of 0.472. Compared to the deviations of the nine segment shell, the mean of deviations is much smaller while having a wider spread. The smaller mean can be attributed to the lack of boundary loops which was included in the nine segment shell, resulting in a spray path which more closely agrees with its initial design. A major contributor to the wider spread of deviation is the aforementioned additional accumulation at the edges due to the walls of the timber frame forcing slurry to rebound and slump towards areas of the thin base shell (reflected in the red halo near the boundary in Fig. 14). The set of horizontal ribs located close to the upper edge in Fig. 14 can also be seen to have additional material, corresponding with the additional edges added during the Eulerisation process of the rib network. Much of the material in these regions were removed during the manual corrections and modifications stage in order to visually match the design. These two regions are the main cause for the higher spread of deviation compared to the nine segment shell. Further deviations are introduced by the distribution of sprayed slurry within the spray strip; as more material is concentrated at the centre of the spray strip as opposed to the outer regions, this leads to a moulded rib as opposed to a flat rib as specified in the design. The effects of this can be seen in the plot of deviation: the sprayed ribs are typically higher near their centrelines and tapers towards their sides, and nodes form mounds as opposed to square protrusions. This shows the limitation of the spray model used; where no overlaps are present, the non-uniform distribution of sprayed material accumulates to form a mould as paths are layered. For the ribbed shell, the effects of this on the achieved thickness are minimal compared to the material piling at the boundary and repeated rib spraying.

6.3. Discussion

The ARCS fabrication process was used to create two sets of prototypes (totalling ten segments). Leveraging the advantages of the high throughput of a concrete sprayer, each segment took less than 30 min to spray, with smaller segments taking only 12 min to spray. Analysis of the thickness of the fabricated prototypes shows that ARCS is able to accurately produce variable thickness curved shells with ribs. Multiple factors contributed to deviations from the intended thickness of the segments:

1. the discrepancy between the measured slurry output and that which was assumed when generating the robotic code,
2. extraneous material deposition during traversals between paths and through connections,
3. the separate treatment of the boundary (for the nine segment shell),
The two different approaches to forming the ribs were both able to deposit material to form protrusions on the shells’ intrados. For the shallow ribs of the nine segment shell, the slicing approach was chosen, as the width of the ribs equalled the width of several spray strips and their heights were relatively small. As such, treating them as additional shell volumes stacked on top of the base shell yielded similar results to that of the base shell and was therefore susceptible to the same factors (i.e., additional material deposition from connecting paths). However, the errors arising from the slicing of the base shell volume are not accounted for in the ribs’ shell volumes. This results in the accumulation of errors as the ribs are sprayed on layered slices as opposed to the designed smooth surface of the base shell. It is expected that this source of error can be minimised by taking into account the sliced profile of the layered base shell into the base target surface for the ribs. For the thin ribs of the ribbed shell, the simplification of assuming a uniform material distribution from the spraying head becomes problematic, due to the lack of overlapping spray strips, and resulted in mounded ribs as opposed to rectangular ribs. Taking into account the distribution of the sprayed material from the spray head (a factor which can change depending on the concrete mix viscosity as well as the make of the concrete sprayer) will allow for more accurate modelling of the designed element prior to fabrication.

Issues regarding precision were identified from setup dependent factors such as the reliability of the air supply and the calibration of the slurry output rate. Integrating digital control of the concrete sprayer with the robot would help to mitigate this, and would also increase repeatability for producing large volumes of the same components. Additionally, variations in fibre content and slurry output throughout the process can further optimise the shells for lower embodied carbon. A simplified version of this has already been implemented to spray the face coats and the base of the ribbed shell which does not include any fibres. However, being able to have finer control would enable unique opportunities for structural optimisation, such as varying the fibre content across the depth of a shell to increase overall utilisation (i.e., concentrating the fibres in the extreme layers and reducing fibre content at the mid-depth).

The spray trajectory planning approach presented can be extended to work with holes and voids to create even more optimised structural components. This can be done by trimming the spray path isolines using the internal shell boundaries, an example of which is shown in Fig. 15. Further work is required to ensure that the connecting paths used to traverse between isolines and layers avoid such boundaries. In addition, as the sprayed material does not have a distinct boundary, the internal voids will not exhibit sharp borders, deviating away from the layered spray model.

7. Conclusions

Thin-shell concrete structural elements have traditionally posed manufacturing challenges, due to the complex formwork and material deposition process. With the additional complexity posed by the inclusion of ribs, such structures have become commercially unfeasible despite being one of the most materially efficient structural forms. ARCS provides a fabrication process which allows the manufacturing of curved and ribbed GFRC structural components at high throughput. Two sets of prototypes fabricated using ARCS were detailed in this paper: a nine segment shell spanning 4.5 m by 4.5 m and a thin shell with deep ribs. Both prototypes showcase the versatility of the process and the production speed afforded by robotic concrete spraying.
Using the implemented Grasshopper3D plug-in in conjunction with the HAL Robotics Framework, robotic code can be generated that is able to accurately deposit GFRC onto formwork surfaces. The novel trajectory planning and layering approach implemented in ARCS was also presented, leveraging geodesics as distance functions in order to generate constant distance isolines on a surface.

While the design process has only been used in conjunction with one physical fabrication setup, it is general enough that it can be applied to any robotic assembly system with a concrete sprayer attached to it. In an offsite manufacturing centre, it would be beneficial to use a gantry mounted robotic arm, which would reduce the limitations on size and reach imposed by a six-axis floor mounted robot. This would facilitate parallel casting of multiple pieces at once (limited only by the reach of the gantry and the size of the workspace). Further increases in the flexibility, repeatability, and accuracy of the fabrication process can be enabled by integrating the concrete sprayer’s calibration, slurry output rate, as well as air supply with the digital control of the robot. In addition, adding a vision system would enable real time feedback on the thickness distribution of the piece during fabrication, which can allow the fabrication process to better adapt to unaccounted factors and reduce the dependency on the accuracy of the machines’ calibration.

Further work is required in order to tune the mix design used to fabricate the shells. The high cement content of the slurry used leads to a higher embodied carbon value per weight of material compared to conventional concrete mixes. Although this is more than offset by the ability to create thinner and more optimised members, the result of which can drastically reduce the overall carbon impact of the structure, further savings can still be achieved by lowering the embodied carbon of the slurry mix. Independent of the mix design employed, ARCS offers the potential of enabling expressive and materially efficient structural ribbed concrete shells to be fabricated at an industrial rate.

CRediT authorship contribution statement

Mishael Nuh: Methodology, Software, Validation, Investigation, Visualization, Writing – original draft. Robin Oval: Conceptualization, Methodology, Validation, Investigation, Writing – review & editing. John Orr: Writing – review & editing, Resources, Supervision, Funding acquisition. Paul Shepherd: Writing – review & editing, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Mishael Nuh reports financial support was provided by the Cambridge Commonwealth European and International Trust.

Data availability

Additional data related to this publication are available at the University of Cambridge data repository at the following link doi:10.17863/cam.85112.

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Appendix A. Supplementary data

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