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Challenges in designing and fabrication of a thin concrete shell

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Abstract

Complex forms, that in history have always been challenges for architects are now becoming familiar to people working at the edge between architecture and structural design. This is, in particular, true for free form shells design. Before the digital revolution, the shell complexity was statically determined through funicular chains, and physical modelling was an essential part of the design process. Today the growth of computer modelling is accelerating the process. However, fabrication and prototyping are still essential part of the process. The growth of the additive and subtractive manufacturing industry opens new avenues for shell design as the design process can be fine-tuned through the use of Building Information Modelling (BIM), and the manufacturing process can be carried out by robotics. Thereby free flowing shell forms once too complex for traditional construction methods can now be imagined through the additive manufacturing process. This paper, presents the exploration of freeform surface through the use of Rhinoceros and its plug-ins. Three thin concrete shells, namely a continuous, a reticular and a waffle like shell are compared in terms of structural efficiency. Additive manufacturing techniques are explored for their fabrication, with a scaled ABS model produced as proof of concept. The combination of these innovative design and construction techniques aimed to produce a sustainable structure that develops strength through geometry.

Keywords: additive manufacturing, continuous shell, form finding, reticular structure, waffle like shell.

1. Introduction

There is an innate elegance to a shell structure's aesthetics; characterised by a free-flowing structure with a continual span, smooth curvature and fluid appearance (Richard Liew & Shanmugam [1]). Shells are natural forms, which can be seen throughout the biological world due to their advantageous characteristics. They have been chosen by species from completely different animal groups; birds and reptiles use shells to protect their young, and creatures like crabs and snails use shells as amour to protect themselves from predators. Their high strength to weight ratio and high stiffness means a strong structure can be created using relatively little material leading to shells' ability to span large distances indicating their efficiency and sustainability.

Breakthroughs in digital design software have created a new world for architects and designers who as a result of these advancements now have complete design freedom, with the ability to produce mathematically precise depictions of curves and freeform surfaces in computer graphics. Similarly, the world of 3D printing has come leaps and bounds over the past few decades. Advancements in technology have brought new avenues for additive manufacturing as new types of material are now available for printing. With the introduction of steel and concrete to 3D printing, architects and engineers now have the opportunity to optimize the use of materials in concrete and steel structures, as well as the potential to elaborate more complex geometries. With these new futuristic methods of construction there is an opportunity to explore new possibilities for their application, one possibility of which is their functionality in the construction of free form shells.

A form-passive structure holds its shape when subjected to varying loads, such shells carry loading through membrane action which can entail either pure compression or a combination of compression and tension (Adrianssens et al. [2]). The advantages to membrane action originate from the absence of bending or very low bending within the structure, which is derived from the three-dimensional in-plane resistance to external forces. For concrete shells in particular, the presence of bending causes tension to build up in the extreme fibres of the concrete which consequently leads to cracking. The occurrence of cracking can be detrimental to the stability of shells as they are considered as imperfection-sensitive structures meaning that they can fail as a result of material non-linearity (ter Maten [3]). There are generally speaking very few occurrences of shells failing, and when failures do occur it is rare that their failure can be attributed to buckling. In most cases shell failure results from poor design and/or workmanship of labour, additionally it is not uncommon for shells to perform better than anticipated when subjected to unpredictable loads (Ramm [4]).

The innate load bearing qualities that shells possess are a resultant of their funicular form, while this paper investigates shells as sustainable structures, the application of funicular forms to building elements can be implemented to improve material efficiency throughout a structure. This was demonstrated effectively by the Block Research Group with their investigation into the application of a rib-stiffened funicular form to a floor system. The research not only implemented digital design to structurally optimise a funicular floor slab but carried out the fabrication using additive manufacturing techniques to produce discrete prefabricated units. The aim of 3D-sand-printed floor was to utilise geometric flexibility thereby reaping the full benefits that accompany the additive manufacturing process. The application of a combined digital design and fabrication process produced a form that paid close attention to functionality and economic feasibility as demonstrated by a 70% reduction in self weight. The implementation of 3D printed sand brings beneficial insight into future applications to more robust construction materials like concrete. The opportunity to reduce the self-weight of building elements offers a sustainable solution to building design, implementing digitally designed funicular forms can lead to the overall weight reduction of an entire building opening up an opportunity to create bigger and bolder structures (Block Research Group [5]).

There are a variety of numerical form finding techniques on offer to produce funicular forms and as a consequence, since the turn of the millennia shell structures have seen a new revival due to processes like finite element analysis significantly simplifying shell design. Numerical modelling provides high accuracy systems as a result of standardised interfaces and interchangeable formats which allow the designer to not only easily create form and seize intricate geometries but, also, analyse the structure and transmit the information to Computer Aided Manufacturing for fabrication (Eisenbach [6]). The most relevant numerical form finding techniques include: Finite Element Method (FEM); Force Density Method (FDM); Thrust Network Analysis (TNA) and Particle Spring (PS) Systems.

This project aims to debates the challenges in designing and fabricate a 8x8m thin concrete shell structure. It investigates the efficiency of 3 shells: a thin continuous, a reticular and waffle like shell. The methodology adopted is based on 3D modelling in Rhinoceros 3D , form finding in Grasshopper/Kangaroo and analysis in ROBOT.. The study envisages the use of self compacting 3D printed concrete for the development of three this shells. However, the limitation of the current 3D printing techniques, did not allow the fabrication of the envisaged structure. As such, as proof for the geometrical concept this paper sees the fabrication of a scaled model in ABS.

2. Digital Design

Gaudí, Isler and other great shell designers all used form finding techniques to help them develop new ideas for funicular forms through an array of different methods. While such methods were vital for the development of fresh designs, in this project simplicity in design was desired. To ensure that the fabrication process is straightforward and uncomplicated, the required shell was designed to be simplistic without any irregularities and symmetrical in the hopes that the forces acting internally throughout the shell would be equally symmetric meaning that no one side is subjected to any higher loading.

Kangaroo, the plug in for Grasshopper is the digital tool's form finder which utilises the numerical form finding technique of particle spring systems. Particle spring systems require discretization to function, which entails the division of a continuous model into a finite number of masses; these masses are referred to as particles and are connected to one another by perfectly elastic springs. The components that make up a particle spring system include: particles that change position and velocity; springs that behave according to Hooke's law; forces that are applied to the particles; and anchor points which are selected particles that do not change position essentially holding the digital model in place. Particle spring systems can often be an ideal method for form finding as they act entirely through axial forces, which is ideal for the creation of shell structures. Kangaroo's particle spring system allows for both direct and parametric interactions during the simulation; this means that forces, anchor points and spring properties can be manipulated directly or parametrically linked to particular parts of the digital model. Kangaroo's workflow operates through chaining a set of functions together, each stage interlinks, and the initial functions are required to ensure that the later functions run accordingly (Tedeschi [7]). Figure 1 shows a flow diagram depicting the stages of form development from initial geometry to final geometry, and the intermediate functions required to cultivate shell form.

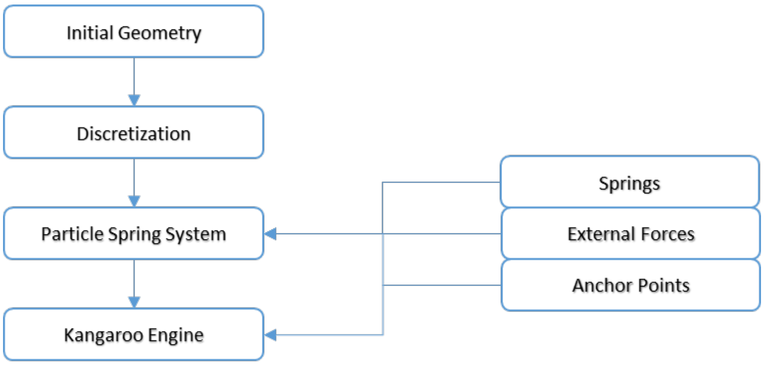

Figure 1 - Workflow of Kangaroo

The Digital design process begins with an initial geometry, this originated in the form of an 800x800 mm surface. The surface undergoes discretization and is split up into a predetermined number of particles, however Kangaroo is unable to process NURBS-surfaces or NURBS-curves and therefore must be converted into lines (points) and meshes (lines) respectively. Once discretization has occurred, the lines are converted into springs and the points into particles. Vectors are then applied to the particles, which represent forces, and anchor points can be defined to represent the supports of the structure. The particles with their applied forces, springs and anchor points are then linked to the kangaroo physics engine and the simulation is run until an equilibrium state is reached. The output from the Kangaroo engine is then represented in Rhinoceros 3D as mesh surface (Tedeschi [7]). The steps required to carry out the design on Grasshopper are outlined below (Tedeschi [7]):

Step 1: Outline an initial geometry – a quadrangular eight-metre pavilion.

Step 2: Define the anchor points – the anchor points were determined to be 4 square supports at each corner of the surface characterised by 9 points on the Rhinoceros interface. This allocation meant that just over 25% of the structures edges would act as a base to ensure stability.

Step 3: Discretization – the division of the surface is initialised by converting the surface into a mesh with a predetermined number of points, 20 points in each direction were selected to build up a mesh made of 400 points. The mesh's edges and vertices were then obtained by external components by Weaverbird, to allow for the conversion of the edges into springs and the vertices into particles.

Step 4: Particle Spring System – the first part of the system that needed to be defined is the spring: after discretization, the edges were connected to the connection input parameter; and the rest length was defined as a multiple of the start length and altered by a factor, a slider is used to manipulate the shape of the structure during the simulation. As the anchor points have already been defined they just need to be assigned to the 'closest point' function that allocates an anchor to the closest point on the surface. Finally, the external loading is assigned to the particles, which is carried out by a force function that allocates an adjustable factor to the particle thereby loading it. Similarly, to the rest length factor, the force factor can be altered during the simulation. Direct interaction with the model was chosen for the design to ensure the end product met the needs of the project.

Step 5: Kangaroo Physics Engine – The final step of the form finding process is to connect each of the particle spring system components to Kangaroo's physics engine and the simulation is activated by a Boolean toggle. The meshed surface, anchored by its predetermined support points is deformed by the external loading and this force is resisted by the springs, the particles then continually moves until the simulation has reached an equilibrium state. The entire grasshopper algorithm is schematized in Figure 2.

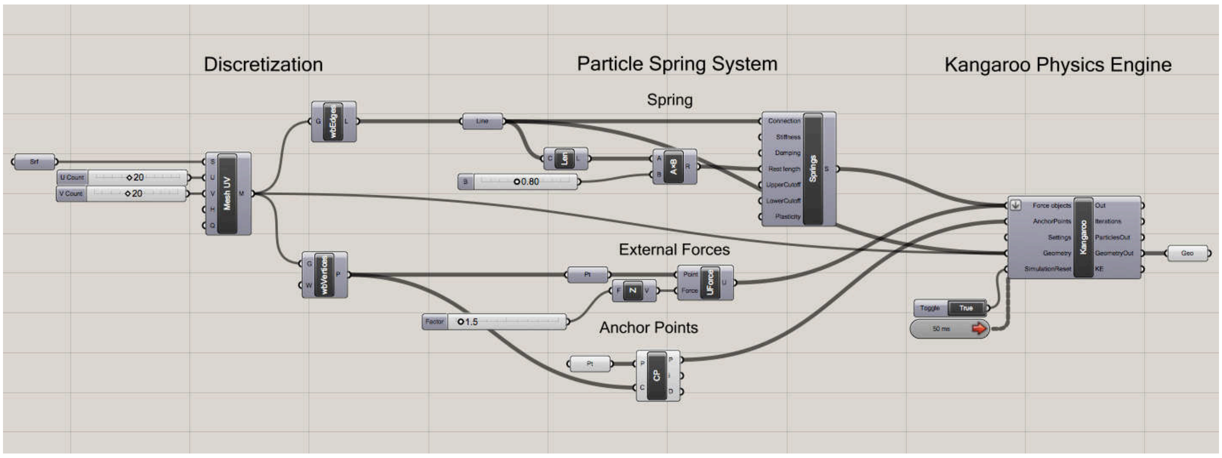

Figure 2 - Grasshopper/Kangaroo workflow of form finding process

Once the simulation is finished the geometry is defined (see Figure 3). This form is created as a result of the particle spring system numerical form-finding technique. ,At this current stage, there is no cross-section associated with the geometry. The factors used to manipulate the particle spring system were reached through a process of design. In particular, the limit considered to generate the geometry f this pavilion were: 8m x 8m plan, with one opening at each edge, height of the opening at least 1.9m, to allow an individual to pass through. The overall height of the shell would then be found through optimisation of the numerical form finding technique to ensure the shell behaved under mainly compression initiating membrane action. The final dimensions of the designed shell (Figure 3) are 8mx8m in plan, maximum height of 3.8 m and maximum height of the openings is 1.9m.

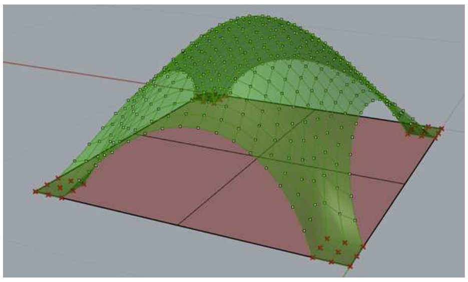

Figure 3 Designed shell

3. Analysis of three thin shell structures

To determine the structural behaviour of the shell the output from Rhinoceros was analysed in ROBOT. Within ROBOT the shell cross-section; material properties and loading cases were applied to the shell. The structure created through form finding in Grasshopper is a mesh surface, which transforms into a collection of bars and nodes forming a net. To understand the significance of shell thickness and determine the most efficient cross section a variety of different forms were analysed, these include: 1. a simple reticular shell made of concrete ; 2. a continuous uniform shell surface; 3. A waffle like structure, obtained as combination of the first two forms. Each structure was analysed with the same class of concrete (C30/37) to ensure they were comparable. Concrete was chosen as an ideal building material thanks to its advantageous compressive strength characteristics. Finally, each shell had the same support conditions composed of the nine points, as outlined in section 2 of this paper, and each support was fixed.

3.1 Loading

Each structure was analysed under an arbitrary live load applied to the shell apex of 10kN to represent the load of roughly 15 people standing on top of it,. As such a $Design\ Load = 1.5\times 10 = 15kN$ with the addition of factored self-weight was considered. At this value, this loading covers the recommended loading of $0.4kN/m^2$ as outlined in the Eurocode 1 when concerning maintenance for roofs (Eurocode 1 [8]).

3.2 Analysis & results

The thicknesses of each shell type were designed, aiming to having buckling as potential failure mechanism, Kanta [9] states that an efficient shell will have an $R/t \geq 336.4$ to ensure buckling initiates failure. The designed shell form has a radius of curvature that constantly changes. At the apex the radius of curvature is at its smallest of 0.187m and gradually increases as it moves down the shell, the radius of curvature is at its greatest when the shell structure changes from concave to convex at the edge; at this point R = 3.01m. For the reticular structure the shell thickness was designed to the worst case and therefore when R=3.01: $t = 3.01\times 10^3/336.4 = 8.9mm$, rounding to the nearest 5mm for ease of fabrication, the thickness for a shell structure should be roughly 10mm. The continuous structure was designed in accordance to the average radius of curvature of the structure (*R=1.599)* and therefore the continuous shell structure was allocated a thickness of 5mm. The final waffle like shell structure was defined as an amalgamation of the first two mechanical models. To investigate whether a waffle structure is more efficient than its continuous counterpart the continuous shell was thinned to a 3mm cross section and superimposed onto the $10mm^2$ bars of the net structure. The volume input for the 'Continuous Structure' compared to the 'Waffle Structure' is $0.29m^3$ and $0.21m^3$ respectively, while the actual amount of concrete saved is minute, proportionally the structure change indicates a 30% reduction of material input; at a larger scale this would prove to be far more significant. To determine the effectiveness of each structure type, the nodal displacements have been analysed and are shown in Table 1.

Table 1- Table showing the ROBOT output of the relationship between shell type and node displacement

Shell Type	Reticular (Cross-section: $10mm^2$)			Continuous (Cross-section: 5mm)			Waffle (Cross-section: 3mm Shell +7mm Net)		
Displacement	UX	UY	UZ	UX	UY	UZ	UX	UY	UZ
Max (mm)	1035	1035	412	2	2	1	4	4	3
Node	214	74	435	230	410	57	230	410	297
Min (mm)	-1035	-1035	-3349	-2	-2	-3	-4	-4	-6
Node	228	368	221	212	22	221	212	22	221

The ROBOT analysis shows that reducing the shell thickness and combing it with 'Net 1' displacements double when compared to 'Continuous 1', but there is a significant reduction in displacement when compared to 'Net 1'. It seems to suggest that the continuous shell structure gives significant advantages in reducing shell deflections. For a reduction in material input of 30%, a small increase in displacement which is only nominal seems to be beneficial. Interestingly Figure 3-13 (left) shows that the membrane forces acting within the Waffle structure increased reaching 63kN/m at the apex, it suggests that due to the thinning of the shell surface, it carries a greater proportion of the load. Figure 3-13 (right) shows a decrease in moment distribution from 0.01 kNm/m to 0 kNm/m for the 'Waffle' structure when compare to 'Continuous 1', this would suggest that the net structure is carrying a greater proportion of the moment and the continuous shell is carrying a greater proportion of axial loads. Essentially, the parts of the shell with a deeper cross-section carries more bending forces than the thinner sections, resulting from the slightly longer leaver arm. While realistically the shell would be a homogenous structure, the distribution of forces to sections which are better equipped to carry certain loads would occur. At this scale the continuous shell seems to be the ideal solution for shell design, the material saving properties of the waffle structure are relatively negligible. Furthermore, while the 5mm shell was proven to be more than sufficient to carry the applied load the difficulties in fabrication of a 5mm shell surface would be problematic; full compaction would be challenging, and the occurrence of any imperfections would no doubt lead to failure. Consequently, the application of a 10mm would be beneficial for fabrication purposes.

The aim of these analyses is not to investigate the capacity of the concrete material, but rather the funicular form that derives strength from the geometry gained as a result of numerical form finding. The efficient use of materials helps to prove the effectiveness of digital design and the inherent efficiency it possesses, providing its argument as a sustainable structure. To determine the effectiveness of the shell design found using particle spring systems, an applied load was carried out on the structures apex similarly to the analytical tests prior. Rather than applying a variable load representing a real-life situation, a design variable load was applied to the apex of the structure to simulate the application of an unusual singular force applied to the shell in order to test how much force the structure could take prior to failing. To determine when failure of the continuous 10mm shell structure occurred observation of nodal displacements were analysed.

Table 2 - Table showing nodal displacement of chosen shell under failure inducing loading scenario

Shell Type	Continuous Shell (Cross Section: 10mm)		
Displacement	UX	UY	UZ
Max (mm)	45	45	27
Node	231	431	296
Min (mm)	-45	-45	-96
Node	211	21	221

Table 2 shows that the failure inducing design load of 1125kN leads to an apex nodal deflection of 96mm (~95mm). This significantly large point load would no doubt lead to the complete crushing of concrete at the load application with membrane forces reaching heights of 4423kN/m at this point. However, considering such an intense load has only caused a deflection of 96mm to the structure with horizontal displacements of 45mm maximum, the shell structure carries the load efficiently and proves the strength that can be found in geometry. The relatively small size of the shell structure brings advantages to the ability to carry load, the distance means that the flow path to the supports is short; this combined with the strength in geometry means that for the applied load the bending moments acting on the shell is minimal, see Figure 4.

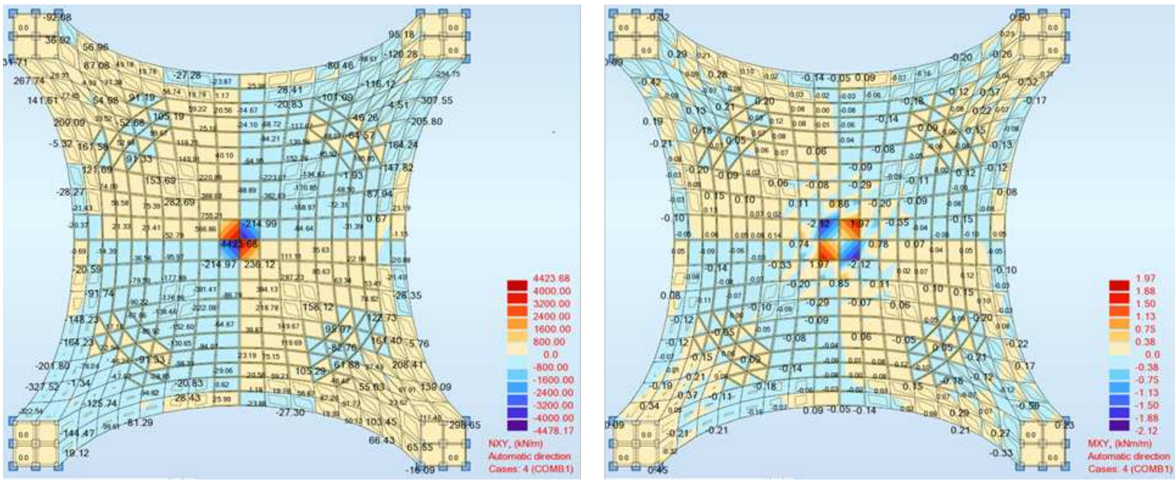

Figure 4 - Map showing the distribution of membrane forces (left); and moment (right) within chosen shell structure

4. Fabrication

To help realise the capabilities of digital design using numerical form finding, a plastic model of the structural shell pavilion was fabricated using additive manufacturing techniques. While this project was unable to investigate the additive manufacture of concrete to curved surfaces, there was still an opportunity to develop a deeper insight into the advantages that accompany the digital fabrication process. To fit within the constraints of the 3D-printer the pavilion model needed to be scaled down to a 1:40 scale model, thereby producing a shell that is 200x200mm in plan.

Figure 5 - Additively manufactured plastic shell

Figure 5 shows the plastic shell model after completion of additive manufacturing; the final outcome shows the impressive technical ability of additive manufacturing techniques to produce a 3D object. The printer's preciseness is apparent in the observation of the mesh texture that was produced through the numerical form finding technique carried out using Grasshopper/Kangaroo. The inclusion of an allocated area to the supports helped to improve the rigidity of the structure which is essential to strength, allowing an efficient flow of force.

5. Conclusion

An investigation into digital design and strength through geometry was carried out with an insight into digital fabrication. This study present the design of 3 thin shells discussing their efficiency and possibility to fabricate them with 3D printing. However implementing concrete into this process was unfortunately not an option due to the limitations that face its application to curvilinear structures. As an alternative to concrete, plastic was implemented to the shell design and a smaller model was developed as to fit within the constraints of the available technology. The plastic model demonstrated the advantages that numerical form finding attributes to strength development and that through digital processing an efficient and sustainable structure can be designed, analysed and fabricated. Most importantly, the process shows that strength is not only derived from the structural material but the shape itself. Considering plastics compressive capabilities are nowhere near that of concrete, finding strength through geometry is even more paramount. The additively manufactured plastic shell shows a good representation of how funicular forms develop strength, the rigidity of ABS is beneficial to the load bearing characteristics as it helps to hold the forms geometry, allowing for activation of membrane action. This model along with the analysis carried out in ROBOT shows the applicability of digital form finding in the creation of a digitally fabricated shell. The next step is to apply additive manufacturing of concrete and improve the strength characteristics of the shell while still implementing digital fabrication.

While additive manufacturing of concrete is allowing first exploration in housing, there are still limitations facing the industry. Providing a concrete with beneficial characteristics to additive manufacturing is problematic. For the process to be possible, a mix needs to be sufficiently fluid to be applied through a nozzle while simultaneously holding its shape once deposited; have characteristics that allow it to set rapidly and gain strength but not cause blockages to the nozzle; and finally have the ability to applied with accuracy and precision. Currently, these requirements are somewhat contradictory and as a consequence these issues are particularly limiting. Further research with concentration on doubly curved structures is required to find a solution.

This project acts as a stepping stone for future applications of the digital design process to develop and fabricate funicular forms, providing guidance for the design of free form shells. Investigations into more abstract forms would be beneficial in the further development of digital processing and the application of additive manufacturing to shell forms is the ideal route for the industry as a consequence of 3D-printings application to complex geometry, as demonstrated in this project. The production of material efficient structures is achievable through a combination of digital design and fabrication, but whether it can unlock sustainable structures is dependent on a comparison between the energy input of new innovations and traditional construction. Nevertheless, this project has indicated the effectiveness of digital processing and outlined the advantageous properties it is aligned with in order to unlock sustainable structures and considering the importance of sustainability as indicated by the UN's Sustainable Development Goals and the Paris Climate Agreement.

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