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Towards Controlled Frustration: Parameterization of Self-Morphing Clay

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Abstract

Motivated by the goal of reducing construction pollution, carbon-efficient shaping processes are being developed to sustainably shape geometrically intricate spatial structures. One such method is 'Frustrated Matter', a mouldless shaping process that leverages the material's intrinsic properties and typology to autonomously generate 3D shapes through geometrical frustration, potentially eliminating the need for moulds. 'Frustrated Ceramics' (FCC) is a material system composed of two clay bodies with differential shrinkage during firing [1], resulting in shapes with positive double or single curvature. This study aims to expand the shaping variations of FCC materials, including changes in curvature orientation, quantity, and type. Through experimentation and analysis, advanced control features are introduced to dictate and quantitatively define the curvature of resulting shapes. These features include adjusting the relative thickness of sheet materials, incorporating clay grooves, and varying material layering orientations. By providing a quantitative understanding of this energy-efficient 'Frustrated Ceramic' system, this study lays the groundwork for predicting the complex non-linear relations between sheet architecture and its versatile morphing outcomes, facilitating its integration into the architectural realm.

Keywords: architectural-matter, material-forming-optimization, material-system, self-morphing, frustrated-matter, morphology-diverse.

Figure 1: Complex-shaped parametric tiles exhibited in 'Creative Differences' pavilion by 'Automorph Network', at the London Design Biennale (Ofri Dar, Hagar Ofek, and Dr. Arielle Blonder), demonstrating complex control features of the FCC system as defined in this paper.

1. Introduction

In the face of global warming, the urgency to reduce our carbon footprint is intensifying. As the sectors of building and construction account for 36% of final energy consumption and 39% of energy- and process-related emissions, the the United Nations Environment Programme has defined the reduction of the sectors' pollution as a sustainable development goal [2]. A crucial factor affecting a building's pollution during its life cycle is the adaptation of the building skin's morphology and materials to the site-specific environmental parameters. Wishing to optimize environmental performance and reduce overall pollution throughout the building's life cycle, the design of building skins tends towards envelopes with high variability and complex geometry [3], [4]. While an intricately shaped building skin might be energy efficient during its built stage, the manufacturing of such a surface with available technologies creates a substantial ecological footprint. This process demands extensive shaping of surface tiles using heavy machinery and frameworks, such as moulds, leading to significant material waste [5]. Therefore, to reduce the manufacturing process's ecological footprint of intricate structures, the exploration of efficient shaping methods has yielded new manufacturing tools and advancements in fabrication techniques, including 3D printing and adaptive moulds, among others [6], [7].

A growing research interest is put in the development of material systems that enhance inherent material capacities, for the sustainable generation of form [8], [9]. Self-morphing is the capacity of matter to morph autonomously into a desired shape due to geometrical frustration; 'Frustrated Matter' is a novel approach to matter in architecture, leveraging self-morphing capacities towards mouldless shaping processes. While the main objective of conventional structural design is to limit deformation, with the right type of material and typology, deformation can be harnessed as a shaping method. Inspired by nature [10] the concept of shaping by frustration has been studied in the field of soft-matter physics in recent years [11]. It has been demonstrated that the self-shaping of a thin sheet can be "programmed" to autonomously adopt intricate three-dimensional configurations through non-uniform growth processes, as described by the theory of incompatible shells [12]. Various possible triggers, such as temperature, humidity, or electric fields, can initiate this process. In this framework, a sheet is characterized by both its actual and reference geometry, Represents respectively the material's local rest state before and after actuation. The mismatch between these geometries, often referred to as "geometrical frustration," creates internal stresses within the sheet [13]. To reduce these stresses, the sheet adopts a final shape where its actual geometry is as close as possible to its reference geometry. Using the theory of non-Euclidean plates, the elastic energy of a bi-layered morphing clay plate of total thickness can be expressed as the sum of two terms: a stretching term and a bending term. The resulting shape is determined by minimizing the elastic energy and the competition between these two energy terms, which scale differently with thickness (t) . The material and geometrical parameters of the sheet, such as its lateral dimensions, aspect ratio, and thickness, dictate whether stretching or bending is the dominant term. By inducing a specific reference geometry on a sheet, control over its final configuration can be achieved.

The potential of frustrated matter as a shaping technique lies in its ability to produce predictable 3D forms through the utilization of material internal deformations [14], [15], marking a significant departure from conventional shaping techniques. In 2021, this concept was first introduced into the architectural realm through newly developed material systems known as *Frustrated Ceramics* (FCC) [1]. FCC was introduced as a material system comprising a layered combination of distinct clay bodies with different shrinking rates. These flat layered sheets are placed wet in the firing kiln, where they morph into 3D shapes through the firing process. The variations in flat sheet material typology, referred to as "control features," dictate the resulting morphing shape. These control features, such as the aspect ratio and thickness of a sheet, are well-established in various self-morphing material systems and theoretical research. These features have been quantified and tied to the shaping results in the theory using the dimensionless parameter $\widetilde{w}$ [16]**.** This parameter predict the transition in the sheet's resulting shape between uniform single curvature ($k1=1/r;\ k2=0$) or uniform positive double curvature ($k1=1/r1;\ k2=1/r2$) , where $k1,k2$ are the tile's main curvatures and r1, r2 its main radii.

$$\widetilde{w} \equiv w\sqrt{\frac{\kappa}{t}} = \frac{w}{t}\sqrt{A\varepsilon} \tag{1}$$

In this equation κ is the reference uniaxial curvature, ε is the inelastic strain and A is a geometrically determined numerical pre-factor of order unity.

These basic control features have been successfully applied in the FCC system, introducing the possibility of achieving the desired shaping results [1]. However, while they effectively describe simple morphological outcomes, the ability to numerically or theoretically describe a wider range of complex geometric surfaces remains limited. In 2022, another research on the FCC system focused on nature-centered application, studied grooves in the lower shrinkage clay body as a control feature, increasing the resulting curvature [17]. This study did not formalise the relation between grooving parameters, sheet parameters and the resulting shape. So far, research on the Frustrated Ceramics (FCC) system has focused on individual elements and introduced control features that result in simple shapes with simple shaping outcomes. Complex control features such as grooving, cuts, and outline shapes have been explored freely but have not yet been theoretically or numerically formalized.

1.1. Architectural application of the morphing clay

To adapt the system for architectural applications, three key issues must be addressed: shape variability, scaling up the tiles, and predictability of morphing outcomes. A basic simulation tool for visualisation of the non-linear relationship between the sheet features and the resolved outcomes of a single surface is currently being developed, along with initial consideration of gravitational factors, as scaling-up implies [18]. So far, the research of the Frustrated Ceramics system focused on individual elements and introduced control features that result in simple shapes with either a single curve or a positive double curve. This paper focuses on the first key issue of morphological variety by introducing advanced FCC control features that enhance the morphological possibilities of individual FCC tiles. The diversity of morphological outcomes in the FCC system is crucial for an architect's design freedom of structures by material frustration.

The architectural design process for large-scale structures such as facades, canopies, roofing, or indoor partitions typically requires subdivision or tiling, necessitating attention to both the overall structure and the individual tiles that comprise it. Consequently, it is essential to assess the FCC system from two perspectives: first, by evaluating the morphological complexity of individual tiles, and second, by examining the assembled structure to assess the manufacturability of a complete architectural element composed of multiple tiles. Addressing both levels will enhance our understanding of how the FCC system can be effectively scaled and applied in architectural contexts. Tiling complex surfaces with FCC tiles poses a fundamental paradox within architectural requirements. Achieving diverse shaping results necessitates the use of varied tile shapes, which rely on basic control features. Utilizing these features entails changes in the thickness and boundary shape of the individual tile. This necessity conflicts with the need for consistent overall tile boundaries and thicknesses, for constructability and aesthetic considerations. Furthermore, the accommodation of FCC tiles with diverse thicknesses and aspect ratios adds complexity to manufacturing and planning, demanding a support structure adaptable to these variations. Consequently, relying solely on the FCC system's basic control features proves impractical for architectural purposes.

Within the general aim for morphological variability, the objective of this paper is twofold: first, to broaden the shaping outcomes of the FCC system by understanding its architectural and structural use limitations; and second, to lay the numerical foundation for the elaboration of current FCC simulations [18] to include advanced control features over the currently applied basic control features. The paper introduces and numerically defined innovative FCC control features [Figure 1] enabling changes in curvature orientation, quantity, and type within a tile. Those features are: porcelain grooves, which influence the orientation of curvature; material layering orientation dictating the curvature direction; stoneware grooves and thickness ratio of clay layers that enable the expansion of curvature possibilities. Throughout the paper, these features and their effects over the resulting structure will be discussed and illustrated through the analysis of three schematic geometric case studies. These case studies will showcase different schematic structures introducing morphological challenges faced by the system, emphasizing the potential contributions of each design feature in enabling such structure. Additionally, diverse combinations of these parameters within a single tile will be demonstrated, showcasing how they facilitate the realization of intricate and complex curvature. Collectively, these features provide increased diversity and control over the resulting morphed shape while maintaining the tile's thickness-to-edge ratio ensuring structural integrity and aesthetic appeal in architectural applications.

2. Material and methods

The physical samples of the FCC system presented in this paper comprise of Audrey Blackman porcelain (Valentine clays website) and Sio-2 ZUMAIA Stoneware (Sio-2 website).

2.1 Sample Manufacturing Process

The manufacturing process involves: (a) Kneading each clay body separately to obtain material homogeneity (b) Rolling each layer to the desired thickness using a roller equipped with custom-fabricated spacers to ensure uniformity (c) Watering the layers to facilitate bonding (d) Layering the different material sheets (e) Rolling the sheet to the final desired thickness to ensure uniformity throughout (e) Firing the assembled flat pieces in the kiln according to a firing graph, as described in Table 1.

Table 1: fire graph of the frustrated clay

Time (Hours)	1:00	0:30	1:30	4:00	1:30	4:30	2:00	0:13
Heat (Celsius)	70	100	100	500	650	1100	1220	1220

2.2 Testing Sets

Seven testing sets were made from FCC, with each sample manufactured in three copies. Setup dimensions are of pre-fired flat samples; measured curvature is on morphed fired samples.

1. Circular discs of fixed thickness *t=3.5 mm* and varying diameter *D= 25 mm to 100 mm*.
2. Circular discs of varying thickness *t=1.7 to 8 mm* and fixed diameter *D=44 mm*.
3. Rectangular strips of fixed dimensions of *30x150 mm* and overall thickness *t=8 mm*, with a varying thickness ratio of stoneware to porcelain to $m=a_1/a_2=1/8$ *to* $7/1$.
4. Rectangular strips of fixed dimensions of *30x150 mm* and with grooves in the lower shrinkage-rate clay, in varying distances *D=3 to 11 mm;* the set is repeated in three different thickness *t=7,6,5 mm*
5. Rectangular strips of fixed dimensions of *30x150 mm* and fixed thickness *6 mm* with grooves in the higher shrinkage-rate clay, in varying distances *D=3 to 25 mm*.
6. Squares of fixed thickness *t=6.5 mm* and width *w=22 mm* and squares of fixed thickness *t=4.5 mm* and width *w=83 mm* with grooves in the higher shrinkage-rate clay; grooves are in varying angles $\alpha=0$ *to 45 degrees*.
7. Samples with a fixed thickness of *6 mm* and varible aspect ratio *length/wide=l/w=1 to 5*.

Two supplementary testing sets were made using elastomers, which have previously served for the validation of theory [19] by ‘residual swelling’. The material system consists of two polyvinylsiloxane (PVS) elastomers, which will be referred to as green (Zhermack Elite Double 32, *E=0.96 MPa*) and pink (Zhermack Elite Double 8, *E=0.23 MPa*). Those sets served as comparison with clay results, for the verification of FCC outcomes against a bilayer isotropic material of high accuracy.

8. Samples with a fixed thickness of *3 mm* and changed aspect ratio *length/wide =l/w=1 to 5*.
9. Rectangular strips of fixed dimensions of *10x50 mm* and fixed thickness *3,4 mm* with groves in the smaller shrinkage rate elastomer (green) in varying distances *D=0.5* to 11 mm.

2.3 Data Processing

Fired samples were analysed using Autodesk ReCap photogrammetry software, converting multiple photos of each sample into a computed 3D mesh. Subsequently, the computed models were scaled, cleaned, and analysed using Rhino3D and Grasshopper. Data measured for each model included its thickness, lateral dimensions and its two principal curvatures, κ_1 and κ_2.

3. Results and discussion

This section introduces the morphological limitations within FCC system and its basic control features, through three schematic case studies of tiled complex-shaped structures [figure 2]: a single-curved surface with variable curvature amount (k_1, $k_2=0$); an alcove comprised of half a dome ($k_1=k_2$) and a half cylinder ($k_1=x$); and a free-form wall with variable Gaussian curvature (K). Each structure will serve for the demonstration of the possibilities offered by the application of newly developed advanced design features, thus enabling the realisation of the said morphology.

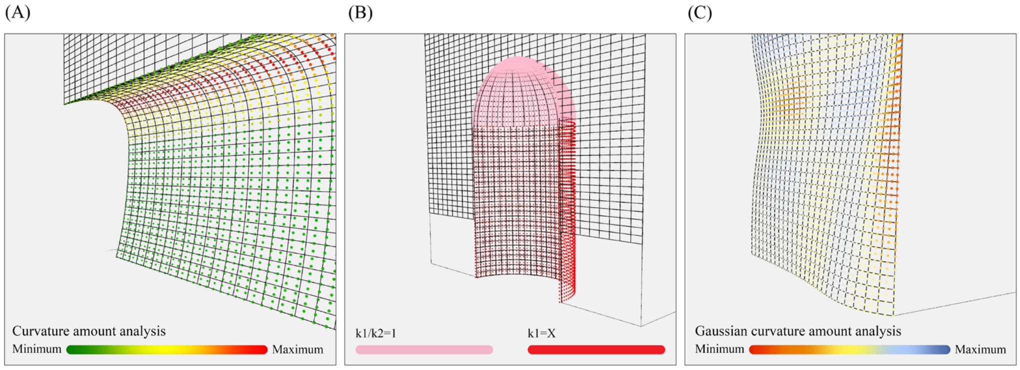

Figure 2: Three structures of building skin , illustrating current limitations of morphing clay system (A) a single curved wall with variable curvature amount (k), (B) an alcove with both half a dome and half cylindrical, (r1=x, r2=0) and (C) a free-form wall with gaussian curvature (K).

Basic control features in FCC include the variation of piece's dimensions (such as discs' radii or a rectangle's lateral dimensions), which result in either double curve ($\kappa_1/\kappa_2=1$) to a single curve ($\kappa_1/\kappa_2=0$) configuration. A set of discs of constant thickness and varying diameters (set 1) demonstrates the previously established transition from a single to double curve ($k1/k2$), as function of the unitless parameter $\widetilde{w}$, quantifying the transition between the two regimes [16]. Though well defined, this basic control feature yields a limited set of resulting morphologies.

3.1. Single curved surface with a change curvature amount

Structure A [Figure 2A] is characterised with variations in the surface curvature amount. The shaping outcome of basic control features in single tile can only result as a surface with uniform curvature. Therefore, tiling the surface with FCC tiles requires rationalising the surface to accommodate non-continuous curvature. This involves obtaining single-curved tiles with varying curvature radii, each maintaining a consistent aspect ratio while varying in thickness. To determine the appropriate thickness, one must calculate it using the equation $|k| \approx \varepsilon/t$ and ensure that $\widetilde{W} > 5.5$, staying within the 'thin regime' to obtain single-curved surfaces only, as shown in [Figure 3B].

Within the thin regime ($\widetilde{W} > 5.5$), basic features of thickness and aspect ratio mainly affect curvature amount. However, a significant influence was recorded on curvature direction in samples of sets 7 and 8 [Figure 3A]. When the tile length and width are similar (close to $l/w=1$), the main curvature orientation tends to be around *40 degrees* to the tile edges. As the aspect ratio increases, the main curvature gradually shifts towards an orientation aligned with tile edges. The change in curvature orientation as function of aspect ratio of lateral dimensions is demonstrated both in FCC and elastomers (test sets 7,8) [Figure 3A] This phenomenon of curvature rotation has been numerically described by Matteo Pezzulla et al. [20]. While there was some deviation between the tested sets and Pezzulla's numerical conclusions, the results demonstrated a similar trend. This newly discovered limitation, linking aspect ratio of lateral dimension with curvature orientation, implies the choice of ribbon-shaped tiles, with an aspect ratio$\gg$ 1. This ensures that the main curvature aligns along the length of the ribbon shape. In conclusion, to manufacture the desired structure [Figure 2a] using tiles controlled by basic features, one must accept the necessity of shape rationalization for the surface, which is dictated by the FCC system. Each tile will possess a uniform curvature amount, and changes in curvature will occur between neighbouring tiles with different curvature amounts. Additionally, limitations on aspect ratio and thickness will dictate the use of tiles with a large aspect ratio and varying thickness.

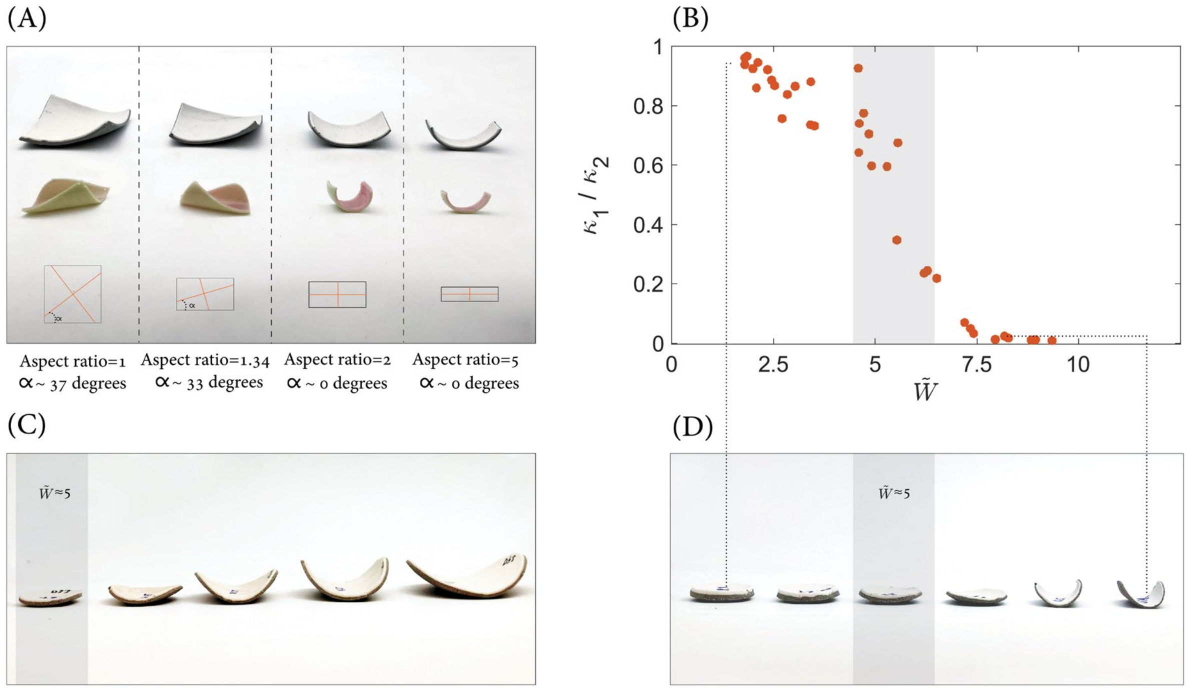

Figure 3: (A) The impact of varying aspect ratio, length/width (l/d) with permanent thickness (t) over the curvature direction. (B) The shape transition dictated by shape ratio (thickness-lateral dimensions) $\tilde{w}$, between a single curvature to positive double curvature. (C) Transition between double to single curved surfaces based on changes of the aspect ratio with permanent thickness, test set 2 (D) Transition between double to single curved surfaces based on changes in the thickness and permanent aspect ratio (thick and thin regimes), test set 1.

Wishing to obtain curvature variation within the single tile, while keeping constant thickness and tile shape (aspect-ratio), two advanced control features were developed: grooving of low-shrinkage clay, and variation in thickness ratio between layers. Introducing grooves in the stoneware creates a mechanical release in the sheet, acting as hinges that allow the material to bend with a higher degree of freedom [17]. The relationship between groove spacing and tile thickness was examined using test set 4, consisting of three groups of strips, each with varying grooving distances *(d)* and permanent thicknesses *(t)*. The outcome [Figure 4C] reveals a trend of increase in resulting curvature up to a critical point around *(d/t=0.75)*, followed by a decrease in curvature with smaller grooves' distancing. To validate the results, a similar, albeit smaller in scale testing set was designed, using pink and green elastomers [testing set 9]. Similarity in trends of various sets of different material systems confirms the increase of curvature with growing density of grooves and highlights the need to further investigate the shift point [Figure 4d]. The second control feature, variations in the thickness ratio of the layers (*$layer_1$ thickness/$layer_2$ thickness=a_1/a_2=m*) relies on the correlation established by Timoshenko [21], relating layers' thickness ratio *(m)* and the resulting curvature of bi-metal strips . Using this principle, the impact of layer thickness ratio on FCC system was investigated (test set 3). Analysis of the results revealed a significant influence of the stoneware-porcelain ratio on the curvature of an FCC strip, reaching its peak around a ratio of m≈0.25 (75% porcelain, 25% stoneware) [Figure 4A]. This introduces an additional control feature with a theoretical numerical establishment that can dictate and influence the curvature amount.

Both advanced features, thickness ratio and stoneware grooving, affect curvature amount and enable higher freedom in FCC system. However, they inevitably lead to a uniform curvature along the tile, and realising varying curvatures necessitates greater tile complexity. This complexity can be obtained through the discontinuous deployment of control features along the tile, as illustrated in Figure 4B. Consequently, the gradient deployment of grooves or layers' thickness along the tile yields various curvature levels, addressing the challenge of tiling a structure with diverse curvature amount (illustrated in test case 1, Figure 2A).

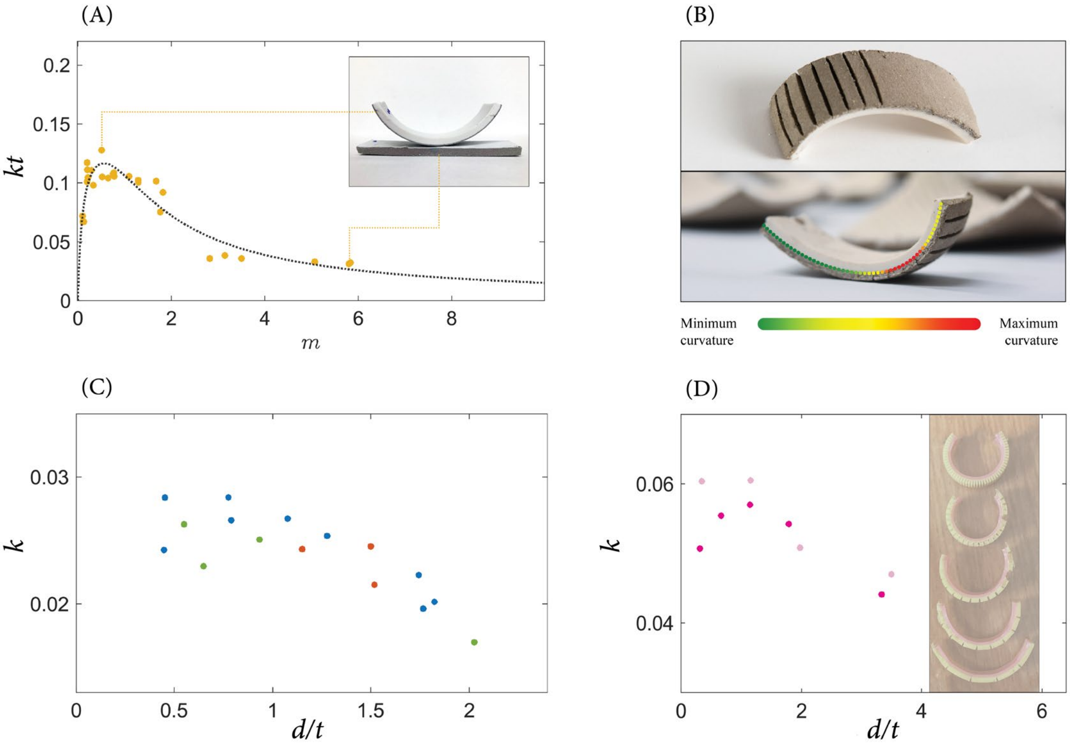

Figure 4: (A) the impact of layers' thickness ratio (m) on curvature amount (B) bottom-curvature analysis showing changes in the curvature (k) amount along the clay tile (B) top-the control feature causing this morphed result is zumaia grooves applied partially along the tile (C) A trend describing the impact of distancing in the stoneware grooves (distancing to thickness ratio, d/t) on the curvature amount (k). Colours represent samples of different thickness (t=5-7 mm). (D) the impact of distancing in the green elastomer grooves (distancing to thickness ratio, d/t) on the curvature amount (k). Colours represent samples of different thickness (t=3-4 mm).

3.2. An alcove with both half a dome and half cylindrical, a single curved shape.

In structure B [Figure 2B] the alcove consists of half dome and half cylinder combined. Addressing the tiling of such a structure using the FCC basic control features involves dividing it into two shapes: half a dome and a cylinder. To obtain a cylinder, tiling a single curved surface, as discussed in the previous subsection, can be easily achieved through a ribbon-shaped tile with $\widetilde{W}>7.5$. Due to the isotropic properties of the FCC system, it is also possible to manufacture a dome-shaped tile with the basic control features. Therefore, a dome-shaped surface can be tiled using the system. As shown in [Figure 1] a dome shape can be reached with small $\widetilde{W}<5$. Small $\widetilde{W}$ implies relatively small width *(w)* and large thickness *(t)* as indicated in Equation 1. This requires the fabrication of thick tiles, which poses challenges due to the impact of gravity and a higher risk of cracking during firing. When attempting to connect the dome-shaped surface and the cylindrical surface to achieve a consistent surface, one will notice that the basic control feature dictates the combination of very thick or very small tiles with respectively very thin or very large tiles. This limitation eliminates the architectural freedom to choose the thickness or maintain a constant thickness, which can impact the overall aesthetic and structural integrity of the facade.

To achieve compatible surfaces of both dome and cylinder shapes while maintaining a permanent $\widetilde{W}$ parameter, the newly introduced control feature of porcelain grooves can be utilised. These grooves determine the curvature direction, as demonstrated in Figure 5(A). Analysis of test set 6 reveals that the grooves do not affect the theoretical reference curvature *(K)* derived from equation 1. Similarly to the stoneware grooves' control feature, here too the distancing of grooves affects the resulting shape. In Test Set 5, strips featuring grooved porcelain at varying distances demonstrate a permanent main curvature along the grooves. As the distance between the grooves is increased, a secondary curvature tangent to the grooves appeares. Analysis reveales that in larger distances *(d>7 mm)*, a discrete curvature between the grooves occurs, whereas in more dense grooving, this phenomenon may occur but may not be visibly apparent. Further theoretical research is needed to fully understand and quantify this behaviour.

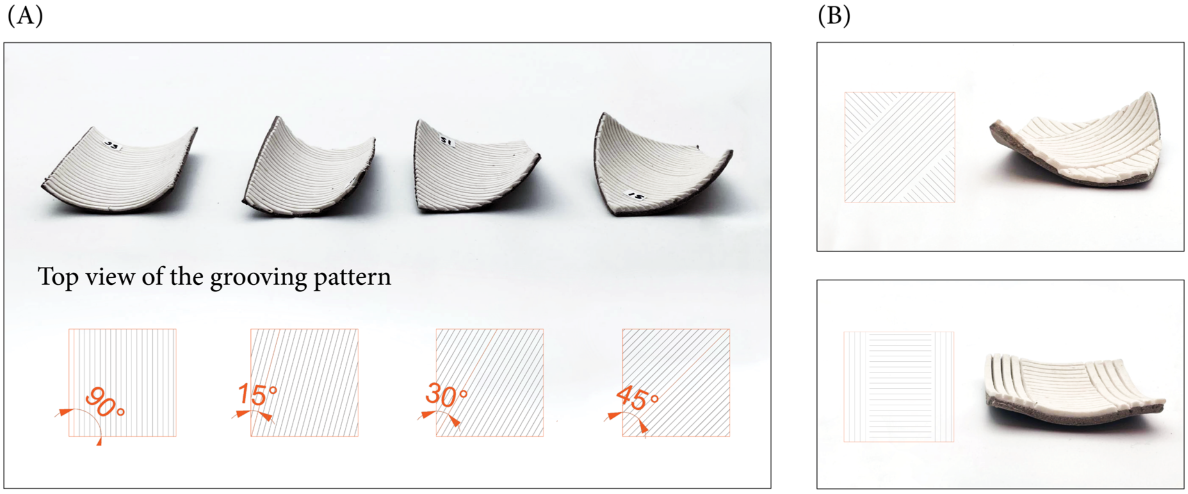

Figure 5: (A) the impact of porcelain grooves on the orientation of the curvature, resulting perpendicularly to grooves' direction. (B) Complex shaped morphing result of combined grooving patterns.

Combining different porcelain grooving patterns allows for the creation of dome shape as well as other complex surfaces, as shown in Figure 6. The ability to control the curvature direction resolves the tiling challenge presented in study case B [Figure 2], thus enables the tiling of the surface using FCC tiles with a permanent $\widetilde{W}$ parameter.

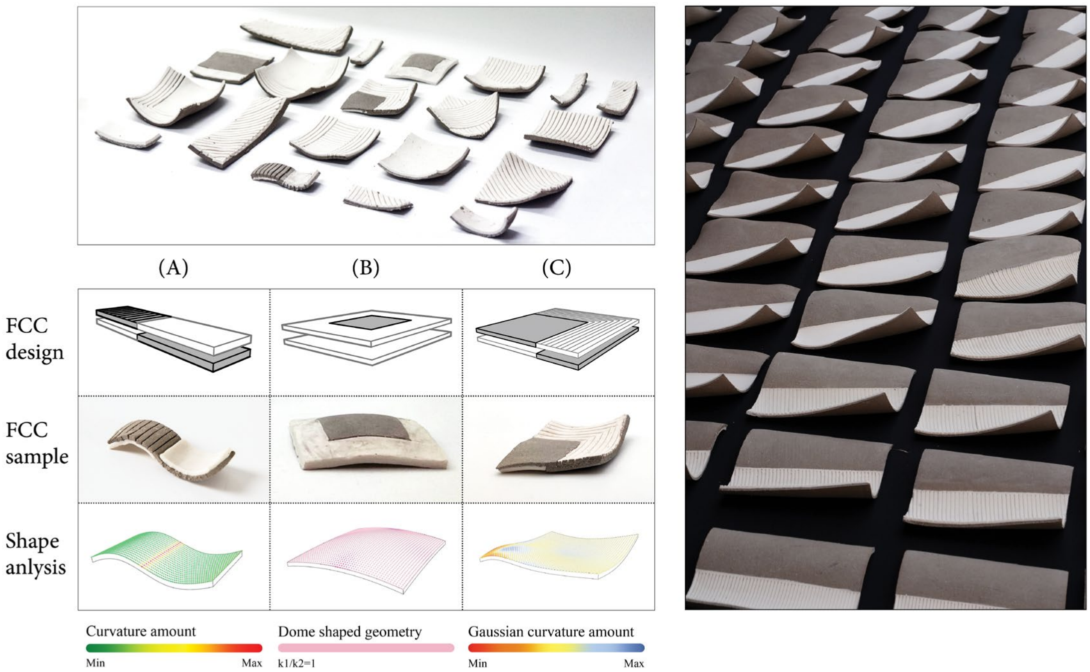

Figure 6: Self-morphing FCC outcomes of different features combination (A) a ribbon with both positive and negative single curvature, (B) a tile, crafted with a novel combination of material orientation, consists of two layers: layer one is porcelain, and layer two is stoneware at the centre, surrounded by porcelain. This combination results in a dome shape. (C) a complex curved tile made from two control feature porcelain grooves and material orientation.

3.3 complex surface

Structure C [Figure 2C], characterized by its free-form surface, presents a challenge in the realm of architectural tiling. Based on FCC system, the complexity of this geometry would require a diverse assortment of tiles, varying extensively in both thickness and shape. Despite the advanced features introduced in this study, designing such a surface remains a challenging task, often verging on the limits of current shaping capabilities of the system.

The successful implementation of Frustrated Ceramics (FCC) tiles for such a structure requires a flexible approach that can accommodate both positive and negative curvatures. This is made possible through the strategic use of material orientation. By positioning the porcelain layer on the reverse side of the tile, the clay sheet is induced to bend toward this layer, achieving curvature in the desired direction as illustrated in [Figure 6A, 6C].

This innovative approach is significantly enhanced by the control features discussed in this paper [see Figure 1], which enable the precise manipulation of curvature orientation, quantity, and type within a single tile. Implementing various combinations of features, within the single tile, expands the range of shaping possibilities, effectively broadening the scope of design and structural aesthetics achievable with FCC. This diversity allows for maintaining a constant thickness-to-aspect ratio while achieving high tile shape complexity, thus offering new avenues for architectural expression and functionality [Figures 1 and 6].

4. Conclusion

This research highlights the Frustrated Ceramics (FCC) system's potential as a sustainable architectural resource, shifting away from traditional, energy-intensive shaping methods. It presents a compelling case for integrating FCC into the creation of architecturally intricate structures by mould-free process through material manipulation. The research detailed here describes and potentially resolves a crucial challenge in developing FCC for architectural use—its morphological variability. Advanced design features introduced in this study—such as grooves in porcelain to direct curvature and grooves in stoneware and variations of layers thickness ratio to modulate it—expand the shaping possibilities of FCC, enhancing design flexibility and optimizing structural performance and aesthetics. It lays the foundation for more complex computational simulations of material-data interactions, enhancing our understanding of the nonlinear relationships between the FCC system's sheet typology and its morphological outcomes. Furthermore, it sets the stage for addressing two other critical aspects: scaling up the tiles and enhancing the predictability of morphological outcomes, currently under study by an interdisciplinary team of physicists and architects.

This research opens several paths for future exploration. These include refining the architectural tiling process to maximize shaping possibilities, assessing how external factors like gravity impact morphological outcomes, integrating advanced features into simulations, and calibrating them with physical experiments. Further studies on the effects of groove depth on shaping outcomes are also anticipated, which will deepen our understanding of FCC's capabilities and limitations, aiding its widespread adoption as an environmentally friendly and versatile material in architecture.

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