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Made by (Material) Frustration

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Abstract | This paper explores the concept of geometrical frustration as an alternative mode of form-making in design and manufacturing. While builders, craft makers and designers traditionally attempt to work with stress-free materials with predictable response and controlled outcome, nature often develops form and function through mechanisms of stress-informed materials. In biological systems such as flowers, geometrical frustration caused by internal stresses often leads to shape transformation. Although scientists have studied and understood this phenomena, material frustration has yet been introduced as a possibility for designers. In this paper, a frustrated materials approach is brought to the design process, through case studies in two different material systems. Both in ceramics and in latex, the material becomes an active partner in the design process, no longer controlled, predictable and "well behaved". Through close collaboration with the scientist, the material's behaviour is understood and analysed for further exploitation, enabling to reverse-engineer surprising new forms.

KEYWORDS | MATERIALITY, MATERIAL FRUSTRATION, MATERIAL RESEARCH, MANUFACTURING, TRANSDISCIPLINARY DESIGN

1. Introduction

Design and Production are control oriented. The history of design relies on the control over materials through manufacturing techniques such as casting and machining, making sure each chosen matter doesn't "misbehave" (Lefteri, 2012). Processing materials involves external tools and moulds, rules and patterns – all created to ensure order and make sure each material element is passive, thus acts according to plan. The need for control is accentuated by computation capabilities, deeply rooted by now in the design and architecture realm, leaving no room for randomness, aiming at minimal tolerance and maximal efficiency, affecting the whole making of a design project: conception, visualisation, simulation, and fabrication (Carpo, 2013).

The ability to generate practically any imaginable form with ease on the computer screen, with digital design tools and advanced visualisation capacities, has led to the ongoing rising challenge of its materialisation as built or manufactured artefacts; designers and manufactures alike face the challenge of fabrication of complex geometries (Kolarevic, 2005; Austern, et al., 2018); issues of cost, sustainability and geometrical limitations come into play, raising significant barriers. The realisation of complex shapes in large scale, typical to contemporary architecture, is furthermore challenging due to the extensive use of moulds in the fabrication process (Hickert, 2016); It is echoed by the large efforts of research and technological developments in the past decades, oriented towards the development of alternative fabrication methods (Sheil & Glynn, 2011; Menges, et al., 2017). While some concentrate on new technologies, such as 3D printing (Duballet, et al., 2017), other directions of development focus on the opportunities to be found in the material itself. Inspired by the philosophy of new-materialism (Miller, 2018) on one hand, and technological advancement in material research on the other, a rising awareness of matter's generative power is at the centre of design discourse in the past years, under the concept of 'Materiality' (DeLanda, 2015). Seeking innovation and alternative modes of form-making, material-systems are developed, where the inherent capacities of the material itself are enhanced and exploited to achieve performance (Menges, 2012). Such material-centred approach widens morphological expression, promotes efficiency and higher performance, and inherently introduces new design paradigms (Hensel, et al., 2010).

Alternative modes for achieving form and reaching required performance, introducing concepts such as self-organisation, growth, hierarchy, redundancy and resilience, inherently relate to the world of nature (Speck, et al., 2017). In the search for alternative modes of form materialisation, nature serves as a source of inspiration and bio-mimetic development processes. While builders, craft makers and designers traditionally attempt to work with stress-free materials with predictable response and controlled outcome, nature often develops form and function through mechanisms of stress-informed materials (Weinstock, 2010). Wishing to adopt alternative material formation processes from nature, requires a shift from the traditional engineering efforts of balancing and annealing residual stresses within materials (Withers & Bhadeshia, 2001), to the study of the principles of stress-driven formation, for possible control.

A growing number of bio-inspired material systems are developed in recent years, mostly looking at biological models, extracting their principles of operation and translating those into a synthetic designed realm (Knippers, et al., 2012). This paper presents an ongoing transdisciplinary research that draws its theory and ideas from the world of non-linear physics into the world of design. From the physical formulation of complex form generation and motion mechanisms in nature, an analytical theory was generalised, applicable across scales and materials. This paper will present the application of the theory of incompatible shells on two very different material families, rubbers and ceramics.

2. Material frustration as shaping mechanism

2.1. Learning from Nature

Much of shape transformation in natural system is driven by internal stresses. For example, the opening of a flower, the swimming of a jellyfish and even the beating of our heart, are all driven by the build-up of internal stresses and their release via global shape transformations. The origin of these stresses is *geometrical frustration,* which can be described mathematically. An example that well demonstrates the principles underlying “forming via frustration” is that of the opening of a seed pod. In (Author, 2011) we studied the opening of a dry *Buhinia’s* seed pod. The pod's valves consist of two layers of fibrous tissue, a tissue that expands/shrinks perpendicularly to the fibre orientation upon hydration/dehydration. If the fibres orientation in the two layers would be identical, the entire flat valve would shrink/expand uniaxially, perpendicular to the fibres’ orientation, remaining flat. However, the fibres orientation in the two layers are perpendicular to each other - in $\pm 45^o$ to the long axis of the pod. Apparently, this simple micro-architecture of the tissue, is sufficient to drive the valves' twisting in opposite handedness upon drying – a process that "shoots" the seeds to large distances. To understand the twisting mechanism, we note that upon drying, each layer “tries” to shrink uniaxially. Uniaxial shrinkage of one layer with respect to the other, induces curvature aligned with the shrinkage: If the top layer shrinks along one direction, the composed sheet would bend upward along this direction, similarly to a bi-metal ribbon. Therefore, shrinkage in two orthogonal directions in the top and bottom layers, induces a saddle curvature. However, since separately, both layers are flat, their in-plane geometry does not match the saddle geometry (imagine trying to attach a large flat sheet of paper to a saddle). This incompatibility is the cause of geometrical frustration: the valve can either fulfil its natural (or “reference”) curvature (saddle), OR its natural (reference) in-plane (flat) geometry. It cannot be completely relaxed, thus must contain internal stresses. One immediately sees that the same type of frustration can be generated in different ways, in sheets made of different materials: for example, by gluing together two flexible sheets while they are stretched in orthogonal directions. Like the seed pod, both layers want to shrink uniaxially, in orthogonal directions, i.e., a tendency to form a saddle. This frustrated structure is described in more details in section 3.

Though the tendencies of each separate part of the material are simple and clear, the behaviour of the combined sheet is much more complicated and unpredictable. In order to understand the geometrical and mechanical behaviour of such a frustrated sheet, one has to develop a suitable theoretical modelling.

2.2. Theory of incompatible sheets

Recent developments in the theory of elasticity introduce and develop a new way of thinking, designing and manipulating solids. Within the framework of *incompatible elasticity*, effective theories of rods, plates, and shells were formulated (Efrati, et al., 2009; Aharoni, et al., 2012). In this framework the local intrinsic geometry of a body is expressed with the reference metric and reference curvature. These express the *equilibrium distances* between the elements that compose a solid body. The reference metric and curvature can result from growth, irreversible deformation, or from the geometry and connectivity of the elements that compose the body. The theory expresses the energetic cost associated with deviation from the reference metric (stretching energy) and from the reference curvature (bending energy) (Efrati et al., 2009).

The formalism opened the way to a set of quantitative experimental and theoretical studies of self-shaping sheets (Gemmer & Venkataramani, 2011; Klein, et al., 2007; Santangelo*, 2009;* Author, 2010). Several important notions were determined, based on the new formulation, providing useful *guidelines for the design* of desired shape transforming sheets, often saving the very complex process of solving the nonlinear elastic problem. The theory was successfully applied to many specific structures, including frustrated ribbons with saddle curvature, such as the seed pod described above. Experimental and theoretical study (Author, 2011) demonstrated the ability of the theory to predict a wide range of twisted and helical configurations obtained at different ribbon widths and orientations.

An important notion related to the formalism is "geometrical frustration" (which was mentioned in the previous section). This occurs when the reference metric and curvatures are *incompatible* – they cannot be both realized by a configuration of the surface in 3D. This is manifested by *sharp mathematical constraints,* given by the violation of Gauss-Minardi-Codazzi (GMC) equations. Under such conditions the body will always contain residual stresses. Within the new formalism, the origin of internal stresses is clearly "visible” and the conflicting geometries are clearly expressed.

Frustrated bodies have unique properties. Any cut or change in the shape of their boundaries results in a change in their 3D shape. This is due to the fact that any configuration is a compromise, set by the competition between the reference metric (stretching energy) and reference curvature (bending energy). Any change in the boundaries of the sheet changes the balance between the conflicting geometries, and a new equilibrium configuration is achieved. This responsiveness and shape variation of frustrated sheets is in a sharp contrast to ordinary stress-free sheets that stay as they are, when cut or curved. This property makes frustrated sheets much more interesting than ordinary ones. A non-trivial information is encoded within them, making them buckle and wrinkle into 3D shapes and to respond in a surprising way to cuts. To some extent such structures are unexpected, but with the theory of incompatible sheets, that holds the information about the reference geometry (in the form of the reference metric and curvature), we can "understand" the frustration of the materials and guess their response.

3. Making form by material frustration: case studies

In mirror of the new physical understanding of generation of complex curvatures in geometrically incompatible, or frustrated plates (Efrati, et al., 2009) and shells (Author, 2011), we developed two experimental design projects: ‘Frustrated Materials’ and ‘Frustrated Ceramics’. These two case studies served as demonstrators of the physical theory, as well as a starting point for future design development. The case studies described in this section operate in two very different material realms, demonstrating the application of similar sets of principles, which rely on the generalised theoretical basis of incompatible shells. From surface design in latex, a soft and flexible material, to morphology in ceramics, a malleable material but brittle once fired, the two case studies will demonstrate the agency of material frustration.

Figure 1. Frustrated Material’, 31 latex tiles. Bet Binyamini, September 2018. (photo: Shay Ben Efrayim).

3.1. Frustrated materials

Frustrated Materials' is a composition of 31 latex tiles (36x36cm each), forming an ornamental wall-piece (Figure 1). Latex is an elastomer, used here in the form of thin (cast) sheets. It is a continuous, homogeneous and isotropic material, with a typically high stretching capacity. Here, this capacity was used to introduce directionality in the material, stretching the latex sheet to one direction only. By the bonding of two sheets, stretched in perpendicular directions, we introduced geometrical incompatibility in the system, as described in section 2. The two stretched and connected latex sheets make a bi-layered material that is frustrated, each layer tending to shrink in opposite directions. Attached to a frame and geometrically incompatible, the bi-latex surface is charged with energy. Once incisions are introduced on the surface, the stored energy is released through the spontaneous generation of three-dimensional shapes. The articulated and ornate surfaces of the 'Frustrated Materials' tiles were made by laser-cutting of different patterns, of stretched bi-layered latex material. To accentuate the bi-layer effect, we chose a top layer of uniform cream colour, and a bottom layer of varying colours (Figure 2).

Figure 2. Surface design by material frustration. The bi-layer structure is accentuated by the choice of contrasting colours between the layers (photo: Shay Ben Efraim)

The case study explored the design potential of controlled shape generation in the bi-layered latex surfaces, through the variation of a few elements. The effect of three main parameters can be demonstrated through the work:

Radius of curvature of the surface - Three elements are related (Efrati, et al., 2009): curvature (K) of the surface (expressed as $1/r$), thickness (t) of the material, and the differential strain (ε) (unitless, $\frac{\Delta L}{L}$ as the percentage of stretch of the material), expressed as

$$K \cong \varepsilon/t \text{ or } r \cong t/\varepsilon$$

This formulation indicates that the typical radius of curvature of the shapes that would form by the cutting of a frustrated surface, could be directly dictated by the thickness of the material used, and the amount of stretching applied (applicable as long as the material is considered 'thin surface' physically). Through a short series of samples, we identified a typical radius of curvature that would be expressive and enabling: significantly visible curvature, without reaching strongly curved forms. Based on a series of initial tests, we aimed for a typical curvature diameter of 8-10mm, being expressive, while not too curly. As we used a latex thickness of 0.4 mm, (the total thickness (t) being 0.8mm), we aimed for a differential stretching (ε) of around 15-20%, that would result in typical curved shapes of 8-10mm diameter, identified as our desired range (Figure 3). (A stronger stretch resulted in more curly or highly twisted shapes, a weaker stretch would result in less pronounced curvature, closer to flat surfaces).

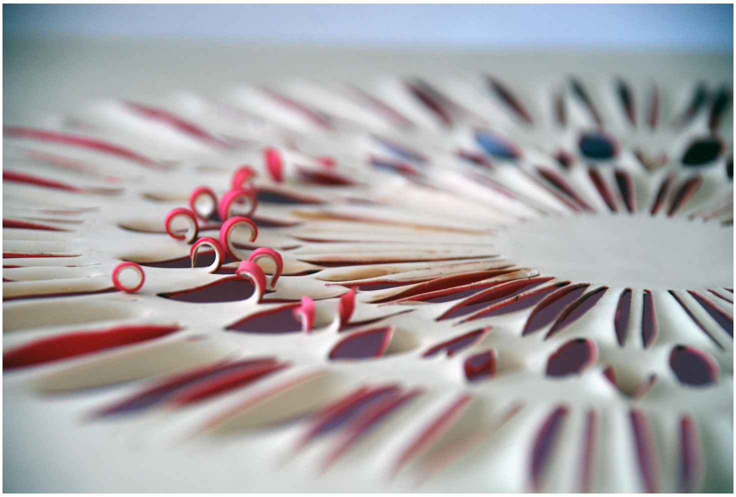

Figure 3 Selecting the radius of curvature by the amount of stretch applied over the material (according to given thickness).

Orientation over the surface - The scientific work of (Author, 2011) showed that the frustrated sheet tends to bend into a saddle-like configuration. The shape of strip cut strip out of this surface would vary according to its orientation over the surface (angle θ with one of the stretching directions), acting as a portion of a saddle-like curved surface, i.e. an identical cutting curve would generate different shapes, depending on its orientation over the sheet (θ) (Figure 4). Following that principle, the 'Frustrate Material' tiles were designed with mandala-like patterns, all with radial organisation. The radial array of an identical cutting curve, was used to express the variety of shapes that form out of the same cutting curve, placed in different orientation: from cylinder-like shapes in either direction of the stretching (θ=0/90), to saddle-like or helical ones on the biais direction ((θ=45), with an identically repeating curve.

Geometry - (Armon, et al., 2011) have demonstrated both empirically and mathematically that strips cut on the biais orientation ((θ=45) demonstrate two different regimes: "narrow" strips that twist around a straight centreline, and "wide" strips that form helical configurations, as a cut out from a cylindrical envelope. The transition between narrow-strip and wide-strip behaviour was explored in the case study, through the variation of patterns in the tiles. Starting with a set of basic graphic elements that generated different shapes, we established a set of "building blocks", or "letters", with which an infinite variety of patterns could be composed.

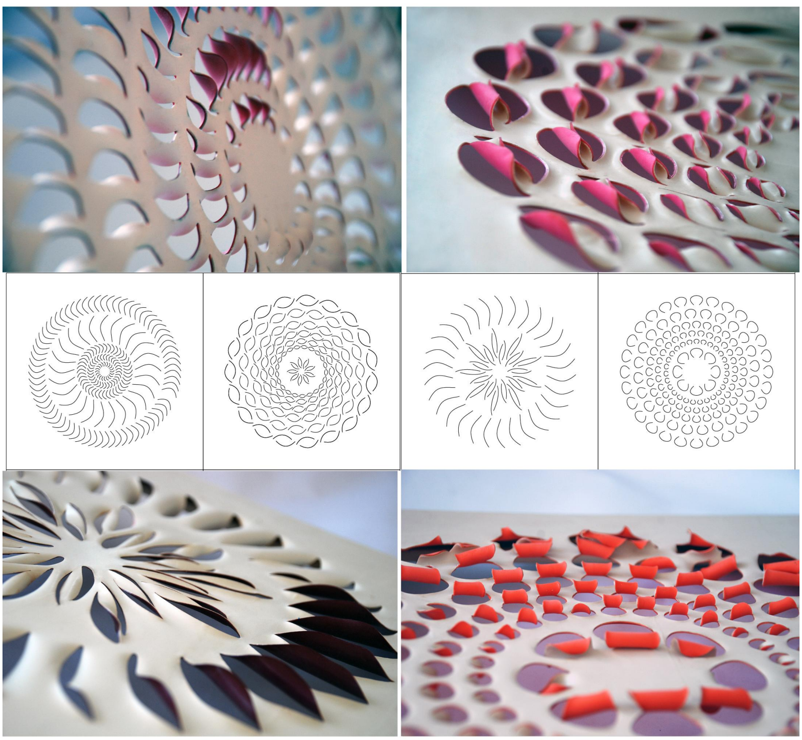

Figure 4 - Rotational patterns accentuating the effect of orientation on the surface over the resulting shape.

The rotational “mandalas”, along with the biological references of frustrated formation of leaves and petals, have led us to the theme of flowers as the visual concept for the tiles. The patterns were conceived with regards to a flower type (Dahlia, Sunflower, Carnation, Thorn, Chrysanthemum etc.) (Figure 6) planning its three-dimensional outcome by using the “building blocks” that we have established in earlier stages (Figure 5). ‘Frustrated Materials’ can be considered as one whole piece and at the same time as a series of tiles; it is a showcase for the scientific work, while being the seed for creative design exploration.

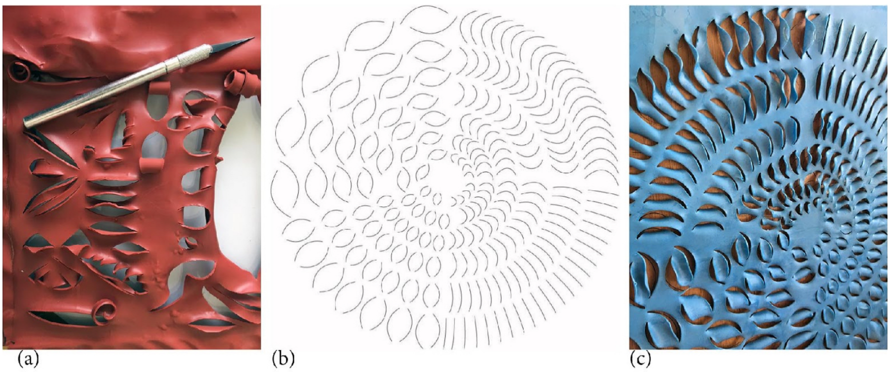

Figure 5. Developing patterns (a) manual cutting, creating a catalogue of ‘building blocks” (B) polar array of curves, developing rotational mandala, pattern (c) surface.

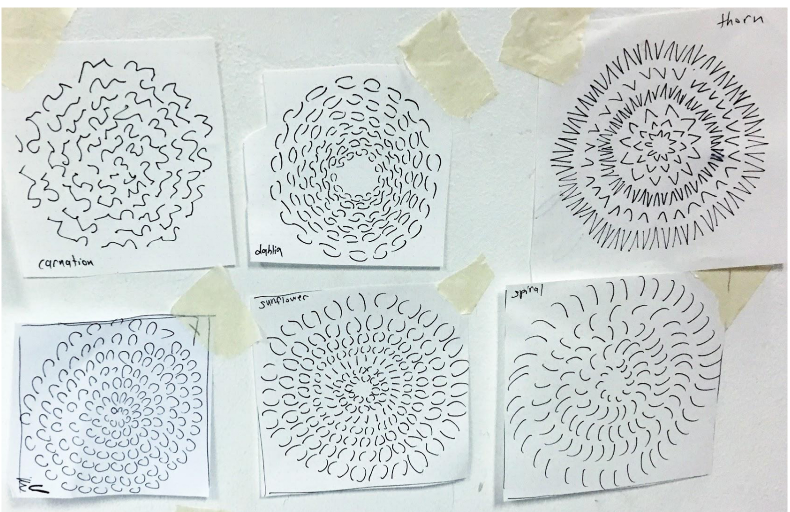

Figure 6. Drafting biologically inspired 'flower mandalas' as inspiration for digital design

3.2. Frustrated ceramics

Figure 7. Series of ceramic material exploration, seeking to accentuate displacement and curvature of the ceramic surface, observed as maximal Z value and minimum radius of curvature

'Frustrated Ceramics' is a series of material explorations that takes the case study of 'Frustrated Materials' as its starting point. Here too, frustration is induced in a bi-layer material, enhancing its natural properties. In the basic ceramic manufacturing process, from the humid chunk of matter (the 'ceramic body') to the accomplished, dry and brittle final stage of the artefact, firing and drying play an essential role. Gradually, water and humidity are released out of the ceramic body in the drying phase, to be then heated in a kiln to bring the clay-body to its full maturity. As moisture evaporates, clay particles come closer and closer together, and thus shrinkage occurs . Shrinkage is substantial in the firing process as well, as glass begins forming within the clay particles (platelets), filling cavities and voids, and reducing volume. The amount of shrinkage is affected by several factors such as type of clay, size clay particle, weight, proportions, size of piece exposure to air, and more. Radical differences in shrinkage within a single piece would lead to the build-up of internal stresses, and are therefore carefully avoided by ceramists, as these might lead to cracking (Reijnders & Centre, 2005).

Wishing to induce frustration in the ceramic material, we utilised the shrinkage phenomenon, inherent to the ceramic process. We combined two material types with substantially different shrinkage rate, porcelain (Audrey 12.5% shrinkage) and stoneware (Terrazo Umbra, 7% shrinkage), bonded to act together as material of bi-layer architecture. The different shrinkage rates within the material introduce geometrical incompatibility (Figure 8) in the system, inducing residual stresses and resulting in large displacements. A flat bi-layered piece entering the kiln for drying and firing process, resulted in a three-dimensional ceramic form (Figure 8). While in the latex bilayer [see 3.1] the material was anisotropic, with directionality introduced by stretching, forming a surface of negative Gaussian curvature (anticlastic), the ceramic material is isotropic and incompatibility between the layers is uniform, forming a surface of positive Gaussian curvature (synclastic).

Figure 8. Flat rectangles of ceramic-body entering the kiln for drying and firing (b) resulting three-dimensional shape.

Aiming to achieve significant displacement to create morphology and maximum scale, series of samples were realised to identify the effect of different parameters over the resulting shape. Parameters related to the ceramic process, such as level of humidity of the ceramic body, positioning in the kiln and the drying-firing curve were examined for their effect over the resulting objects. Scientific principles were implemented through the exploration of geometric properties, such as thickness of the layers, width-length ratio of the element, curvature continuity of the two-dimensional contour and surface grooves, were varied to analyse their effect over the resulting form.

- **Minimal thickness -** similarly to the prior case study, here too the thickness directly affects the curvature obtained by the surface; the thicker the material, the shallower the curvature would be. However, compared to the latex, the wet clay is heavy and soft. This makes gravitation effects non-negligible. Gravity enters the scene, and should be taken into consideration, limiting the amount of curving of large samples. Therefore, we aimed at minimal thickness of the bilayer, within the possible range of the clay material (typically, 2-4 mm for each layer).
- '**Narrow ratio' - length to width -** In relation to the overall thickness and gravity, another geometrical consideration would be the ratio between the circumference and the surface area, i.e. the width to length ratio of the piece. The narrower the

piece, the smaller the frustration is; the conflict between lateral flatness and curvature is minimised. A more significant curvature in the long direction can take place, which is only weakly “resisted’ by the tendency to flatness of the in-plane geometry (the reference metric) (Figure 10). We therefore prioritized narrow and long geometries, to achieve significant morphologies.

Figure 9. From flat sheets to shaped ceramic, illustrating geometrical incompatibilities: the matching curves in the flat sheet transform to non-matching edges once frustration is in play.

- **Oscillating curvature** - A large number of shapes can correspond to the definition of long and narrow. We have noticed that the geometry of the contour of the shape affects the obtained curvature of the surface, and a clear preference was noted to outline curves that had oscillating curvature, forming a kind of S shape (Figure 11). While this behaviour was clearly observed in samples, its origin is still unclear from the theoretical point of view and is the subject of new mathematical and physical research at the lab these days.

Figure 10. Prioritising long and narrow shapes where lateral frustration is reduced, and significant curvature can take place in the long direction.

- **Introducing grooves** – Due to the isotropy of the ceramic material, the incompatibility within the ceramic surface is homogenous, hence restricting curving as mentioned above. In order to accentuate curving, we introduced directionality in the material through grooves in its stoneware layer, as this layer restricts the movement of the material (as a result of lower shrinkage rate) (Figure 11). Whether inspired by the mechanical reference of a hinge, or biological reference of fibres in the seed pod (see 2.1), the grooves enable movement on the perpendicular direction to the groove, and thus accentuate the curving on this direction.

Figure 11. Oscillating curvature of two-dimensional contour curve creates significant displacement in resulting surface. Grooves on the terrazzo layer enable additional displacement and curvature.

4. Discussion

This paper presents the implementation of frustrated materials as an alternative approach to design and fabrication, through two case studies, in ceramics and soft materials. Although the principle of materials frustration is common in biological systems, known and understood by scientists, it has not yet been introduced to designers as a possible means of creation. By working from the materials' properties, this proposed approach could come as an alternative to the efforts invested in shape generation, creating form becomes simple through a reverse engineering process, once leaning on scientific knowledge. This approach brings new players into the design process: the material becomes active and sometimes surprising and the designer, who works closely with the scientist, no longer forms it alone. Therefore, there is a need for mapping and reorganisation of the design process, which may lead to an alternative methodology and even a new role for designers.

Making by material frustration, suggests a new form of manufacturing. Rather than technological advances it enhances material inherent capacities. Free from moulds, manual labour or new technologies, it suggests an alternative forming process, offering freedom of shape and opening new morphological horizons as well as a detour to serial production. In ceramics, as explored in the second case study, material frustration suggests an alternative to traditional form-making of vessels and may lead to more sustainable possibilities of manufacturing by reducing excessive labour, large quantities and stock.

By reflecting on these two different projects, materials frustration for design may be analysed further in order to outline an alternative design methodology. Frustration may also offer new capabilities for traditional materials. In latex, for example, by generating frustration, structure was introduced to a flat, isotropic, structureless material, thus enabling the material autonomy. Further investigation in the potential of frustrated materials in design could open more possibilities for innovation in materials yet to be explored, such as glass, wood, metals and more.

For designers, utilising frustration in materials requires a shift of control: taking a step back from the drawing board or computer screen and enabling the material properties to lead the way. Following hands-on materials experimentation and research, the design potential of the materials' behaviour may be analysed and later translated for further development - as a bottom-up strategy for design. This strategy not only affects manufacturing methods but may also hold potential for creating original shapes and forms, difficult to foresee or plan in standard approaches. Here, the material is no longer a passive matter which reflects exactly the designer's ambitions. Therefore, this proposed method impacts the role of the designer who should embrace a flexible mindset and reflexive attitude while gaining knowledge of the frustrated material's behaviour, which is sometimes surprising, unexpected and even difficult to understand. A third party, the physicist, can be joined as someone who understands the materials' frustration (knows the principles of the theory of incompatible elastic sheets) and can help the designer with his/her interaction with the material. Once understanding the qualities of the material, the designer may strategically intervene in the process in order to exploit the frustration for the desired results. In the process described in these two case studies, the designer may be seen as an agent, connecting between different partners: expert, materials and tools, to explore innovative ways of making.

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