Material in Performance-Driven Architectural Geometry

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INTRODUCTION

Advanced Computer Aided Design (CAD) techniques have enabled the architectural designer to expand his/her formal repertoire for the built environment and generate non-Euclidian geometries, such as freeform surfaces. Nowadays, designers are encouraged to produce radically new forms, leading to renewed interest in generative design tools that can produce such forms algorithmically and parametrically.[1]

The design process comprises various phases from conceptualization to construction, including structuring of the problem, preliminary design, and refinement and detailing.[2] Today, computational tools associated with performance analysis, evaluation and optimization are utilized during a later stage of the design process, following form generation occurring in the preliminary design phase. Different parties are involved in the design process, including the design and consultant teams, towards the realization of a building. If the architectural form is generated by the design team, the model can then be reviewed by consultant teams, in terms of its engineering aspects, for building performance such as structural performance, building physics etc.

Parametric tools help to remove limitations normally imposed by the interface with traditional architectural CAD packages and enable new possibilities in multi scale design refinement. [3] Various architectural issues can be resolved simultaneously, where different parameters can be incorporated in the early stage of the design process, as in integrated design processes.

Towards the realization of a project, 3D model data of freeform surfaces can be precisely translated into a physical prototype or an actual building component via Computer Aided Manufacturing (CAM) techniques. Nevertheless, these techniques are not fully translated into the architecture and construction industry yet because of their restrictions in terms of material, manufacturing size and cost. Meanwhile, architectural geometry is an emerging field of research focusing on rationalization of freeform surfaces. The rationalization process is widely investigated along with panelization tools, where architectural geometry is subdivided into smaller components.

Although existing literature contains broad research on architectural geometry and panelization tools, they are not able to accommodate requirements related to material properties and building performance. The question of "how material can be integrated into a system where architectural geometry, material and building performance are interdependent to increase efficiency" remains unresolved. To discuss this issue, a parametrically defined architectural surface, a wave surface, is generated, analyzed and evaluated as a case study by the author in which parametric modeling, panelization tools and series of analysis tools including Finite Element Method (FEM) Analysis are used. Different types of materials are tested within specific boundary conditions to assess their structural performance.

Architectural Geometry

The configuration of built forms by Lionel March and Philip Steadman are early attempts to represent architecture, using a numerical representation

of form. Both of them used binary encoding that corresponds to a matrix of cuboids. More complex geometries were also investigated later on. Prous-alidou and Hanna proposed a parametric representation of ruled surfaces that uses a minimal set of variables to represent a wide variety of surfaces. The parametric representation provides significant information in the matrix of values. [4]

In parallel to these works, architectural geometry is an emerging field of research developed by the liberation of freeform surfaces in architecture. This research is positioned between differential geometry, computational mathematics, architectural design and engineering. [5] The intent of architectural geometry is to explore analytical methods to investigate surfaces in architecture.

The classical differential geometry investigates smooth geometric shapes (such as surfaces). On the other hand, discrete geometry studies geometric shapes with a finite number of elements (polyhedral). The theory of polyhedral surfaces is aimed at developing discrete equivalents of the geometric notions and methods of surface theory. The field of discrete differential geometry emerges on the border of differential and discrete geometry. [6]

Rationalization of Freeform Surfaces

To realize complex freeform surfaces, one has to segment the shape into simpler parts, so-called panels. [7] Three methods were explored for the rationalization process in the literature, namely, pre-rationalization, post-rationalization and co-rationalization. [8, 9] Co-rationalization is described as a process in which the compositional system is defined alongside and through the process of designing a form. [8] In the pre-rationalization method, the building geometry is usually predetermined by a number of geometric constraints set in the early design stage. In post-rationalization, the building geometry is simplified to accommodate realistically constructible components in the later stage of the design. [9] Post-rationalization methods are implemented in common architectural practice towards the realization of freeform surfaces. The geometry needs to be analyzed and evaluated with rules of applied geometry for rationalization of the form.

There are various ways to subdivide complex surfaces and built curvilinear forms. Considering discrete

surface solutions, planar quadrilateral panels obtain a number of important advantages over triangular panels, such as having a lower node complexity. Single curved panels can be evaluated as developable strip models which may be considered as semi-discrete surface representations. Other types of semi-discrete representations which are suitable for covering negatively curved surface parts are ruled surface panels. [5] Rationalization of large-scale architectural freeform surfaces with planar, single-, and double-curved panels is a method in which the algorithm computes a paneling solution that meets prescribed thresholds on positional and normal continuity. Total production cost assessments can also be embedded in the algorithm. [10]

The rationalization process of freeform surfaces is currently an emerging field of research along with architectural geometry, which aims to develop new tools and techniques. The number of unsolved tasks is enlarged by the number of different materials being used, because their behavior (performance) and production (manufacturing) technology has to enter the panel layout computation. [5]

Building Performance

Architectural geometry needs to incorporate many requirements of aesthetic, programmatic, functional, technical and environmental aspects. Issues related to building performance can be categorized into four main areas as structural analysis, building physics (thermodynamic analysis, lighting analysis, air-flow analysis), acoustic analysis, and fire engineering (smoke-spread analysis, people-movement analysis, heat-flux analysis).[11]

Formal organization, along with material selection, plays a significant role in building performance analyses. The important aspect for structural engineers is the load applied on the (nodal) connection of members and the stresses that occur within the members. Architectural geometry in any form, including freeform surfaces can be analyzed and evaluated via FEM to specify local stresses in the material. [11] Having complex domains – such as freeform surfaces-subjected to general boundary conditions, the FEM is a powerful computational technique for approximate solutions to a variety of engineering problems. FEM is based on the decomposition of the domain into a finite number of elements where a systematic and approximate solution is constructed. [12]

Design Optimization

Design optimization is used as a decision-making process for building and construction. This engineering design paradigm aims to solve architectural design problems. It is mainly used to generate decisions through iterative interactions between design, analysis, evaluation and synthesis.

In architectural applications, optimization has been used for modeling freeform surfaces that meet with panelization of architectural geometry as previously discussed. Nevertheless, these examples do not consider material and structural performance constraints. Some CAD modeling systems, including CATIA, provide visual feedback from the FEM that indicates the current state of stress. However, they do not guide the user on how to adjust designs for improved stability; manual model adjustment is still required. [13]

BACKGROUND

Performance and Material Aspects of the Integrated Design Process

EifForm provides an opportunity to explore the relationship between associative geometry and performance-driven generative design. The overall structural form is generated in response to a model input by the user and can be adapted to various design alternatives.[14] Evolutionary Structural Optimization (ESO) is developed for conceptual forms of complex structures. It works with the logic of subdividing the surface into discrete geometries and subtracts pieces based on computation to achieve the optimized solution by using the FEM, by removing inefficient materials gradually from a structure to achieve the optimum solution.[15] Procedural Modeling for Structurally Sound Masonry Buildings project is designed to establish a set of physical constraints and a building topology, where an appropriate shape is determined. The user provides a set of production rules that describes the desired architectural style, along with a small set of free parameters. [13]

Although the techniques mentioned above are valuable for investigating form generation and performance aspects together and offer optimization solutions, they are not fully adopted by the architecture industry yet, since they have formal limitations in generating design solutions.

The method developed by Hanna and Haroun Mahdavi uses the FEM as an analytical technique to model the input of a given structure and loading condition where the same principles also guide the manufactured output. The complex internal structure of any natural material can be assumed to be continuous and homogenous on a macroscopic scale. A complex microstructure equivalent to the desired continuous properties of a material is fabricated. [16] The Voronoi Finite Element Method (V-FEM) introduces the act of generation through tessellation informed by material behavior. A quantitative characterization and analysis of property mapping are introduced. Then, they are applied to a tiling algorithm using Voronoi cell tessellation. This approach allows the designer to incorporate the mechanical and other types of properties of material in the form generation process. [17]

Although these two methods are novel in terms of incorporating material properties and performance requirements into the early stage of the design process, it is not possible to translate them into the building scale, yet.

METHODOLOGY

The proposed methodology aims to explore fundamental principles of a relatively complex system which consist of form generation, analysis and evaluation. The intent is to map the critical steps which aid the designer for building freeform surfaces in architectural scale.

Following the form generation, series of analyses were undertaken during the design process, including curvature and smoothness analyses for the surface, planarity analysis for the panels, and stress analysis for the global system. The ultimate goal would be to interlink the analysis and evaluation results to the form, where the form can respond to the requirements related to the material properties, manufacturing constraints and performance. The methodology contains the following procedures:

1. Form generation

2. Surface curvature analyses

3. Panelization & planarity analysis

4. Material selection

5. Imposing the boundary conditions

6. FEM simulation for structural performance

1. Form Generation: Parametrically Described Surfaces

Surfaces, such as sphere, torus, cylinder, moebius strip, catenoid helicoids, henneberg, catalan, elliptic paraboloid, klein surface, enneper and many more can be structured in parametric systems by assigning their respective mathematical curve functions. A wave function has been explored as a case study in the Rhinoceros Grasshopper medium where the code is developed by the author.

First, a parametrically defined NURBS (Non-uniform rational basis splines) surface is generated through the operation of mathematical curve functions assigned in the parametric design medium. The construction curves of the surface are driven through two identical basis functions. The function and the parameters are stated as below:
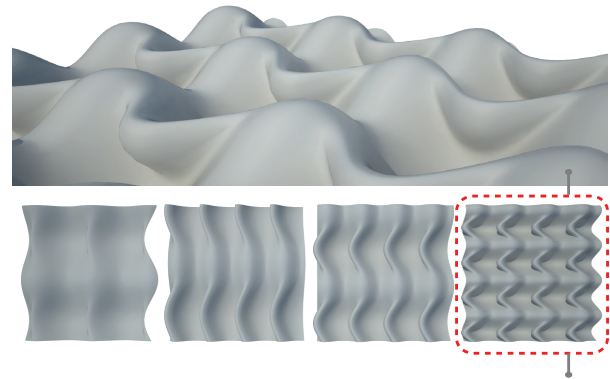
> *Function1 & 2*
> $F = β \times \sin (μ \times X)$
> *Parameters*
> Range values (X, β, μ)
> Rebuild curve values

There are three variables (X, β, μ) assigned to the both functions. The system is able to produce numerous different surfaces within the range values. (Figure 1) Since the surface is considered as a monocoque (structural skin), a feasible option for further studies has been selected which generates structural legs potentially.

The surface with the dimensions of 5 m *36 m *36 m is explored and the values are stated as below:

> *Function 1*: 2.5 x sin (0.7 x 2000) + 2
> *Function 2:* 1.5 x sin (0.7 x 2000)

Once the NURBS surface is generated, another operation is completed by adjusting the U -V curves (divisions in the x and y directions) of the surface. These figures can be increased or decreased based on the design intent and would affect the total number of surface points which is significant for the panelization of the surface.

Function 1: 2.5 x sin (0.7 x X) + 2
Function 2: 1.5 x sin (0.7 x X)

Figure 1. Numerous surfaces are generated via the code at the Grasshopper parametric design medium by adjusting their range values. The feasible option has been selected for further studies.

2. Surface curvature analyses: Mapping surface attributes

After the generation process, the surface is brought into the analyses tools in Rhinoceros to map its surface attributes. Gaussian, Mean, Zebra and E-map tools are operated for the geometry.
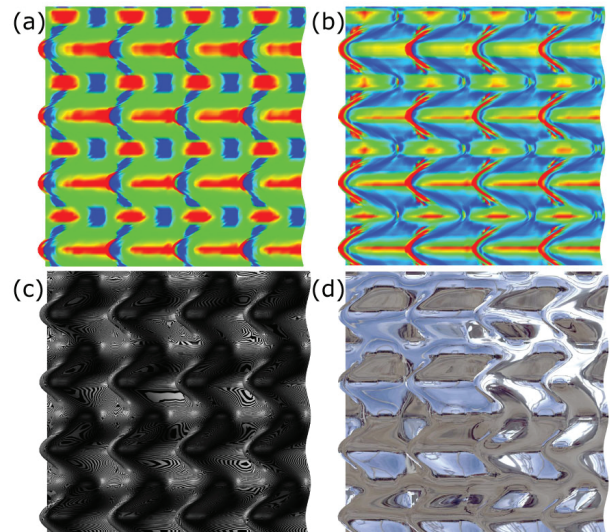

Figure 2. Various analyses are undertaken to identify curvature for the selected parametric surface. (a) Gaussian curvature; (b) Mean curvature; (c) Zebra; (d) E-map

The Gaussian curvature of a surface at a point represents the product of the principal curvatures at this particular point, and the Mean curvature of a surface at a point represents one half of the sums of the principal curvatures at this particular point. Following that, Zebra and E-Map, visual surface analyses tools are operated to check the smoothness of the geometry. (Figure 2)

Through a series of analyses, it is possible to distinguish flat, single or double curved areas on the surface, and surface faults if any exist. If any fault is determined, then there is a necessity to re-construct the surface by tuning the parameters. This operation is crucial to assessing the buildability of a surface.

3. Panelization & planarity analysis

Once the surface is defined mathematically and refined in terms of its surface curvature, it needs to be subdivided into smaller components in order to be manufactured in architectural scale. Since quadrilateral panels have advantages as previously discussed, the wave surface is subdivided via quadrilateral panels where the assigned algorithm, developed by Paneling Tools plug-in for Rhinoceros, determines the panel sizes by evaluating the points on U-V curves associated with the surface topography. By adjusting them, panel sizes can be altered. In the model, the number of points on the U & V curves is 40 * 40.

Following the assignment of panels, the planarity analysis is undertaken, developed by Evolute plug-in for Rhinoceros, in order to map problem areas and achieve planar quadrilateral panels which are feasible for manufacturing. (Figure 3)

4. Material selection

Because material needs to be incorporated into the overall system, the model is investigated further through the FEM analysis medium, Scan & Solve plug-in for Rhinoceros. The material library of the medium currently consists of isotropic materials which have the same mechanical properties in all directions, such as concrete, glass, marble, acrylic, steel, aluminum and various other metals etc. The parameters related to the material for the FEM computation are stated below:

> Failure criterion (*von mises, maximum shear, rankine, coulomb mohr, modified mohr*)

Density
Elastic Modulus
Poisson ratio
Yield strength
Tensile strength
Compressive strength

Three materials including steel, concrete and aluminum are tested in the case study in order to demonstrate their differences in results in the same boundary conditions.
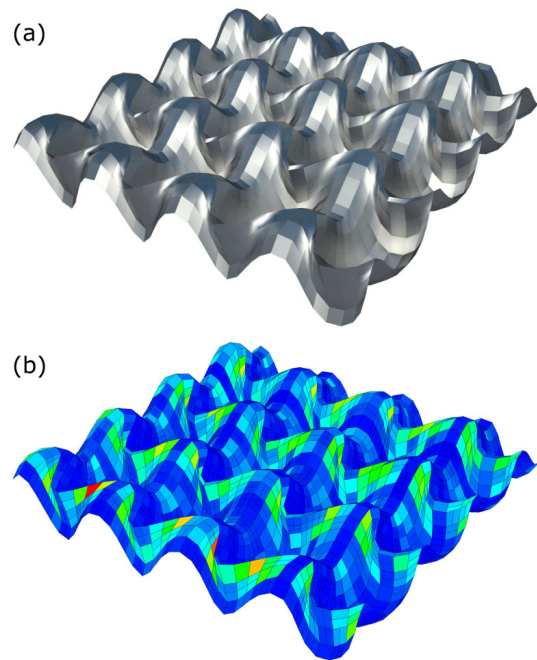
(a)

(b)

Figure 3.(a) Parametric surface panelized; (b) Planarity analysis for the panels

Restrain (x, y, z)
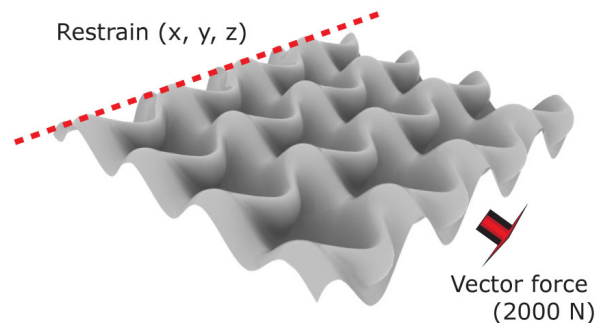

Vector force
(2000 N)

Figure 4.   Imposing the boundary conditions where the parametric surface is restrained on one edge and a load of 2000 N is applied on the opposite edge.

5. Imposing the boundary conditions

Boundary conditions are imposed where restrains and loads are defined along with their quantitative values. The surface is restrained on one side including x, y, z directions. A vector force with a magnitude of 2000 N is applied to the opposite side of the restrained edge. (Figure 4) The conditions are designated simple for the case study, considering actual buildings would require comprehensive boundary conditions.

6. FEM simulation for structural performance: Comparative stress analyses with different materials
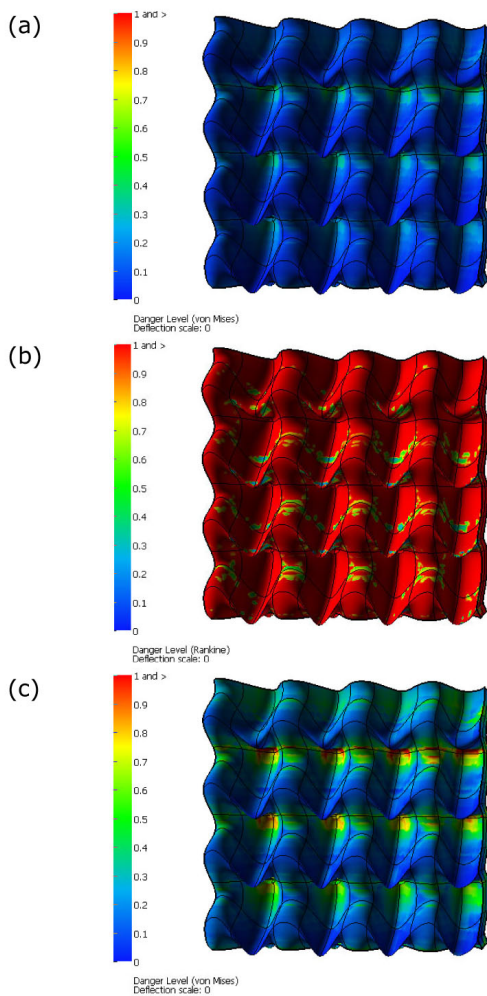

Figure 5. FEM stress analysis for danger levels for different materials used. (a) Steel; (b) Concrete; (c) Aluminum

The deflections can be computed through the FEM for components, including x, y, z displacements, total displacement, max-min principles stresses, stresses xx-yy-zz, von mises stress, max-min strains, danger levels (von mises & max shear stress). Red color indicates danger areas on the surface. (Figure 5)

Scan & Solve plug-in for Rhinoceros operates on solid objects made out of joined NURBS polysurfaces. Because of the current limitations of the FEM software, the NURBS surface prior to panelization is used for the simulation. Selection of multiple solid objects, such as panels in our case, is a challenge which is currently being investigated. I would like to underline that the comparative results would not be affected if the surface were subdivided.

RESULTS AND EVALUATION

By running the FEM simulation, differences in results can be compared and evaluated by the use of three different materials. Whereas steel perform relatively well, the concrete surface is observed to be in danger.

As a commonly known fact, concrete is strong in compression, while metals such as steel is strong in tension. By considering the imposed boundary conditions where the surface is restrained on one edge and pulled with a vector force, the results are significant in terms of the mechanical properties of materials used. Because concrete does not perform well in tension without any reinforcement, the system is not safe, as observed in the simulation.

This relatively simple system has shown how critical to incorporate material properties and boundary conditions of a building into the early stage of the design process. Exploring relationships among architectural geometry, material and performance requirements would allow architectural designer to design by increased efficiency, and also awareness.

SUMMARY AND CONCLUSIONS

Advanced computational design and 3D modeling tools liberated architectural form by enabling the creation of freeform surfaces. Nowadays, architectural designers need top-down engineering solutions to realize freeform surfaces in architectural scale. Architectural geometry is an emerging research field

at the border of differential geometry, computational mathematics, and architectural design/engineering which focuses on developing analytical tools towards the realization of complex forms.

Building freeform surfaces is mainly based on a process of rationalization which is applied to the architectural geometry in a later stage of the design process. Computational tools associated with the performance analysis, evaluation and optimization are undertaken in the phases following the form generation. Current literature contains broad research based on architectural geometry and panelization tools towards the building process of freeform surfaces; however, they are not able to accommodate material and the performance requirements of the buildings.

Systems established through parametric design obtain rules and relationships which are mathematically defined. Relationships among the system elements are set at the beginning of the design process, in which the design problem becomes well-defined, even for a complex system such as building. Bringing issues related to the realization process to the beginning of the design process, architectural designers will be able to deal with form generation, analysis, evaluation and optimization processes simultaneously.

This paper aims to discuss how form, material, structure and performance can be investigated during an early stage of the design process. Parametrically described surfaces are tested along with the Finite Element Method, in which relationships between material, architectural geometry, panelization methods and structural performance are explored.

FUTURE LINES OF RESEARCH

The author is currently developing a fully parametric model which aims to incorporate material properties in the form generation process, along with structural performance and panelization methods. Since parametric representation, such as surfaces as parametric systems, provides information in the matrix of values, all parameters of the building system can construct element matrices where a global matrix can be obtained for the entire system in which the equation can be computed.

The issue of optimization is to be resolved in a later stage of the research where the actual form can respond to the material and performance. The parametric model might be potentially extended in future to include various building performance criteria, in addition to the structural performance. Another aim is to investigate the form generation process further, where the system can obtain richer formal capabilities which can respond to the needs of current architectural practice, not only for freeform surfaces, but for any other type of surfaces.

The research is undertaken for a static system, which is architecture. However, dynamic systems, such as responsive architecture can be also investigated in future for fulfilling further requirements of buildings, where building responses and performances can be implemented into the parametric system.

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