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Performance oriented generative design of structural double skin facades inspired by cell morphologies

Omid OLIYAN TORGHABEHI, Peter von Buelow

University of Michigan
2000 Bonisteel Blvd., Ann Arbor, USA
oliyan@umich.edu

Abstract

This research explores the applicability of a performance oriented design approach for form exploration of double skin tower structures inspired by cellular morphologies. Taking advantage of computer aided design and simulation this paper explores the structural and environmental potentials of using Voronoi space divisions in conception of double skin facades for tower structures.

The geometry of the double skin structure is created by parametric modelling following the principles of cellular division. Optimization software is employed as a genetic based tool for exploration of design alternatives. The software combines parametric modelling, finite element performance simulation, and a genetic algorithm coupled with database storage of solutions.

A SQL database is used to store all of the evaluated design alternatives. The exploration of desired solutions is then performed through database sorts and queries, and a pallet of well performing design alternatives is generated through the exploration process.

Keywords: form exploration, associative modelling, genetic algorithm, Voronoi patterns, seismic design

1. Introduction

The natural world has always been an influential source of inspiration for architects and engineers. Inspiration by nature has contributed to the quality of design in different levels including visual and conceptual level. Through common access to digital and computational tools during the design process, inspiration from nature has contributed to design at the level of computation (Roudavski [5]). With the advent of numerical simulation software and growing tendency for engineers and designers to take advantage of simulation tools in the design process to evaluate the performance of different design solutions, performance based form finding processes have emerged and evolved into an effective design process.

Taking advantage of computer aided design software today the designers and engineers can model complex geometries that emerge in the natural world. Apart from visual attractions of these complex natural geometries, they are the result of millions of years of evolution through which materials have taken their most efficient configuration in the living organism. Due to similarities of the built environment and natural world there are great potentials in using these performative natural geometries in conception of form for the built environment.

In a bio inspired approach this research explores the application of Voronoi patterns in form exploration of structural double skin facades for midrise towers. Voronoi patterns appear all around in nature. At microscopic level they exist in the basic principles of cell division. At the macroscopic level the patterning of giraffe skin and turtle shells have the same principles. Technically, for a set of points a plane is divided into Voronoi cells in a way in which each cell belongs to a specific point in a set of points, and every point in that cell is closer to that specific point than to any other point in the set of points (Dimcic [2]).

As an analogy, building facades in built the environment play the same role as animal skins in nature. As animal skin provides protection against injuries, invasion of bacteria and cold, and it also provides a shield against excessive evaporation of body fluids and regulates body temperature. Similarly, a building façade can be designed to contribute to environmental performance of the building, e.g. lighting, ventilation and thermal performance, as well as structural integrity. In this regard double skin facades have been proved to be efficient in increasing the overall performance of the building.

In a performance oriented form exploration process, this research investigates the possibility of using double skin facades as the main loadbearing system for the structure. While the double skin provides a better loadbearing system for gravity and seismic loading, it also provides a double layered façade which can be designed for environmental performances. This process provides an integrative approach toward the design of multifunctional systems in an architectural context.

For an effective exploration of performative solutions a reliable stochastic search method is needed. In this research a genetic algorithm (GA) has been used to search the solution space in the process of form exploration. GAs are widely used in computational form finding processes. Due to their stochastic nature, GAs can effectively search the design space of highly nonlinear problems (von Buelow et al. [7], Dimcic [2], Baldock and Shea [1], Kicinger et al. [3]). Moreover, observing design evolution can be used as an aid in stimulating designer creativity. The advantage of such an evolutionary approach is the potential discovery of diverse solutions distributed across the state space that meet performance targets by increasing designer interaction (Malkavi [4]).

Genetic Algorithms are used in this research as the optimization engine in the process of form exploration. ParaGen is a genetic based method which combines associative parametric software with simulation and analysis tools such as finite element analysis (FEA) software to build a database of well performing solutions. This database can then be explored both visually and through performance values, to find suitable design alternatives. The goal is to develop a pallet of well performing solutions through the detailed form exploration (Fig. 1). The ParaGen method and details of its utilization can be found in earlier papers (von Buelow [7][8]). This paper shows the use of the method applied to the more complex performance optimization of a Voronoi mesh support structure subjected to earthquake loading.

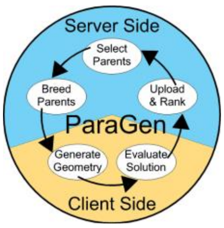

Figure 1: Form exploration cycle in ParaGen

2. Geometry definition

The first step in setting up a form finding process is to define a consistent parametric model with well-defined geometric boundary conditions. This paper explores the form finding of a 20 story double skin tower structure with polygon floors on each story. The floor to floor height of each story is taken as 4 m. At each floor a rigid concrete slab distributes and transfers the gravity dead and the live load to a radial network of steel wide flange beams Fig. 2. These beams transfer the gravity loads to a central column and peripheral steel double skin.

The beams also create semi rigid diaphragms for the story levels to transfer lateral loads to the double skin. The cellular skin is the main loadbearing system for the earthquake loading. In order to design the cellular skin frame for seismic loading the tower is analyzed for self-weight and seismic loads induced by story mass at each level of the tower.

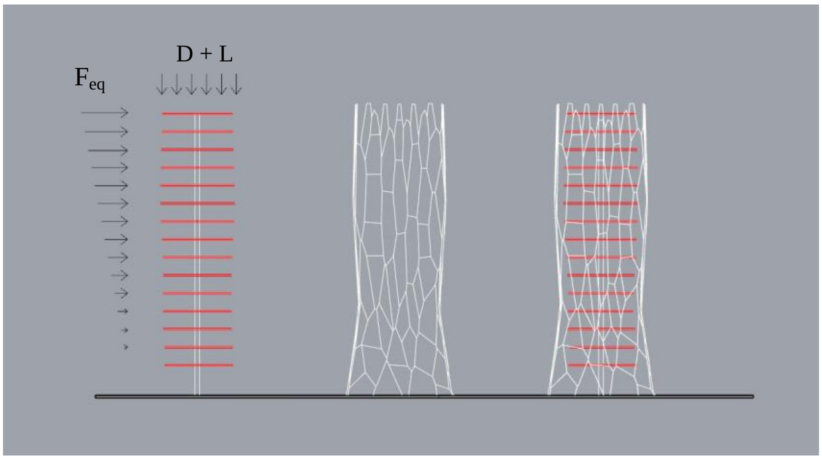

Figure 2: Gravitational and seismic loading and Structural hierarchy.

3. Parametric modelling

The complex geometry of the double skin is created based on three categories of parameters. First set of parameters define the overall geometry of the tower. This set includes a number which defines the type of polygon used as the floor shape which can be a polygon of either three, four, five, six, seven or eight sides. The overall geometry of the structure is create by a multi-section BSpline surface constructed through four polygons placed on horizontal planes spaced at 4 m in the vertical direction. These polygons are created based on corresponding circumferential circles. The radius of each circle is a parameter which can vary between 10 m to 20 m.

The second set of parameters define the local geometry of the skin. A Voronoi mesh has been used to create cellular patterning of the tower skin. In order to create the skin pattern for the structure, Voronoi seeds are laid out on a plane at the bottom of the tower on ten concentric circles evenly spaced from the base story circle to the overall height of the tower which is 80 m.

Voronoi seeds are created based on ten parameters defining number of points which will be placed evenly on each of the ten circles. These parameters control the density and the configuration of the Voronoi seeds in the plane.

Using the procedure described above, seeds are distributed in the XY Plane using a script transaction in Generative Components (GC). A plugin called rcQhull is used to generate a 2D Voronoi diagram based on the distributed seeds (Fig. 3). The density of the patterning of the peripheral skin is dependent on the number of seeds. Subsequently, the vertices of the Voronoi diagrams are projected onto the BSpline surface of the tower and the polygons are regenerated on the inner tower skin based on the mapped vertices.

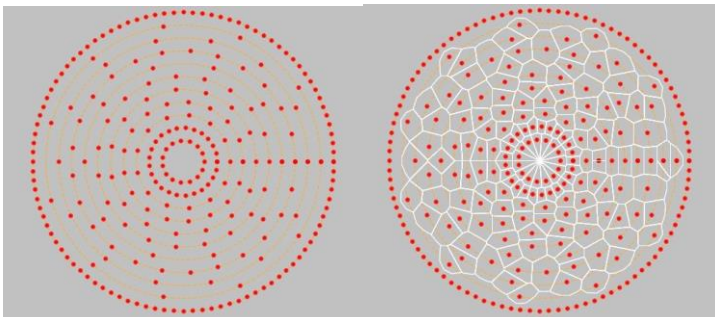

Figure 3: 2D Voronoi Pattern Creation using rcQhull in Generative Components

The outer skin is created by mapping the projected Voronoi polygon members along the radial connection members starting at mapped Voronoi vertices on the skin extending outwards based on the thickness of the double skin defined by a parameter called *Thickness*. This parameter defines the double skin thickness which has effect on the structural as well as environments performance of the structure (Fig. 4).

In order to create the story beams, the structure was cut by horizontal planes at the level of each floor. Radial floor beams were created from the center to the intersection of the planes and structure (Fig. 5).

	A	B	C	D	E	F
1	VARIABLE	VALUE	Min Value	Max Value	Step	
2	Skin_Loft_Radius1	18	10	20	1	
3	Skin_Loft_Radius2	12	10	20	1	
4	Skin_Loft_Radius3	15	10	20	1	
5	Skin_Loft_Radius4	11	10	20	1	
6	Voronoi_Seed_C1	20	8	25	1	
7	Voronoi_Seed_C2	15	8	25	1	
8	Voronoi_Seed_C3	18	8	25	1	
9	Voronoi_Seed_C4	28	8	25	1	
10	Voronoi_Seed_C5	20	8	25	1	
11	Voronoi_Seed_C6	26	8	25	1	
12	Voronoi_Seed_C7	18	8	25	1	
13	Voronoi_Seed_C8	30	8	25	1	
14	Voronoi_Seed_C9	24	8	25	1	
15	Voronoi_Seed_C10	15	8	25	1	
16	Voronoi_Seed_C11	20	8	25	1	
17	Polygon	4	3	8	1	
18	Thichness	1.5	1	3	0.1	
19						

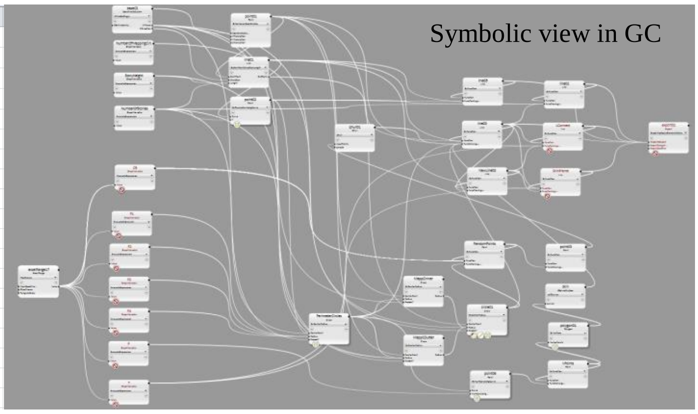

Figure 4: Excel sheet designed to control the parametric variation of the geometry in GC

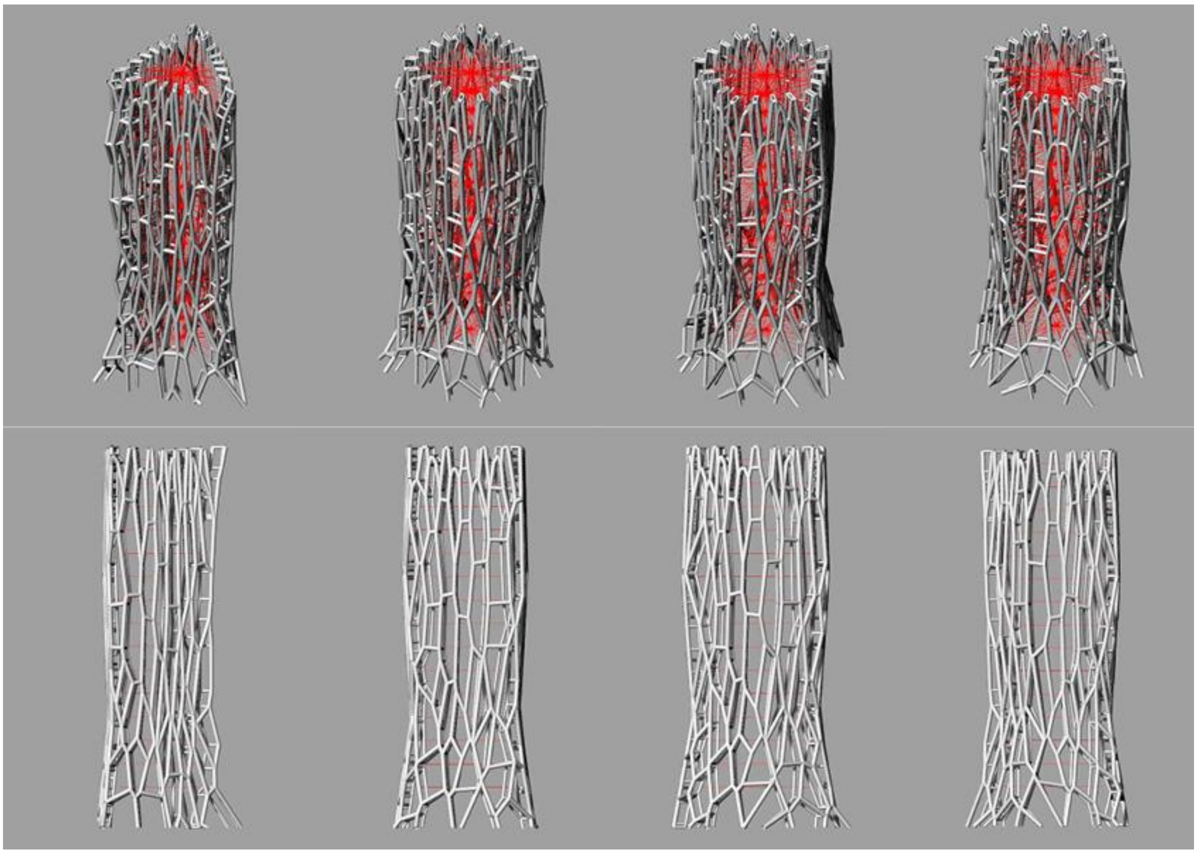

Figure 5: Geometry definition and effect of cross sectional polygon in the local and global geometry of the double skin structure. From left to right, triangular, quadrilateral, pentagonal and hexagonal cross sections.

4. Structural loading

The structure is designed to resist dead, live, self-weight and seismic loading conditions. Dead and live loads are applied to story beams, which transfer the loads to skin members. For the seismic loading, equivalent static lateral force analysis has been used. Commercial finite element software STAAD.Pro, from Bentley Systems is used to carry out structural analysis and design of the structure. Steel HSS pipe sections were used for the skin frame and W sections were used for the story beams and the central column. All connections in the outer shell are considered rigid, with simple connections between the floor beams and the shell. The simple connection will transfer the gravity loads without induction of moments to the skin frame at the point of connection. Using, San Francisco, California as the project site, the seismic parameters are tabulated in Fig. 6, based on IBC 2006 building code.

S_s	S_1	TL	I	R_x	R_y	Soil Class	F_a	F_v	CT	X
2.142 g	1.099 g	10	1	4	4	4	1.0	1.5	0.035	0.75

Figure 6: Seismic parameters based on IBC 2006

The structure is analyzed under gravity and seismic loadings and designed based on AISC-ASD building code. The FEA is iterated to get convergence of member sizes.

5. Form Exploration

ParaGen is used for the form exploration. The method is based on a Non-Destructive Dynamic Population GA (NDDP GA) (von Buelow [7]). ParaGen is "non-destructive" in that it retains all of the generated solutions in a SQL database. Children solutions are bred on demand by dynamically creating populations of parents using SQL queries and sorts. Two parents are chosen from a population at random and bred to produce one child. The child solution is then passed from the server to a machine on a windows cluster in the form of input values for the parametric software (in this case GC). After the geometry is generated by GC it is passed in the form of a DXF file to STAAD.Pro for analysis. The analysis step yields performance data as well as images such as actual member sizes and deflection plots. All of this data is uploaded to the server and stored in the SQL database from which new populations are drawn and the cycle continues. To automate the parametric process of the different runs, AutoHotkey (AHK) is employed. AHK is an open-source scripting utility and automation software that allows users to automate different tasks in Microsoft Windows. AKH script is used primarily to link the various software packages being used (Excel, Generative Components, AutoCAD, STAAD.Pro).

The dynamic breeding populations are drawn from the current database using combinations of SQL sorts and queries that form the multi-objective fitness functions for the GA. In this way, ParaGen uses the NDDP GA to fill the database with a steady flow of solutions which respond to the given fitness criteria. The online database created by ParaGen can be searched using, structured queries based on both performance values and geometry such as base shear, maximum deflection, total weight, and number of members, among others (12 in all). The designer can use these data to sort and explore the solutions for desired combined performance.

Through selective breeding the GA successively explores more "fit" areas of the solution space. The resulting solutions are not only optimized for explicit objectives, but can also be searched by the designer to interactively explore the design solutions and even combine desired solutions through manual breeding.

The process begins with the random generation of solutions (see Fig. 7). After a sufficient number of solutions along with performance values have been loaded into the database the GA begins to use a series of fitness functions based on database queries to build the dynamic breeding populations.

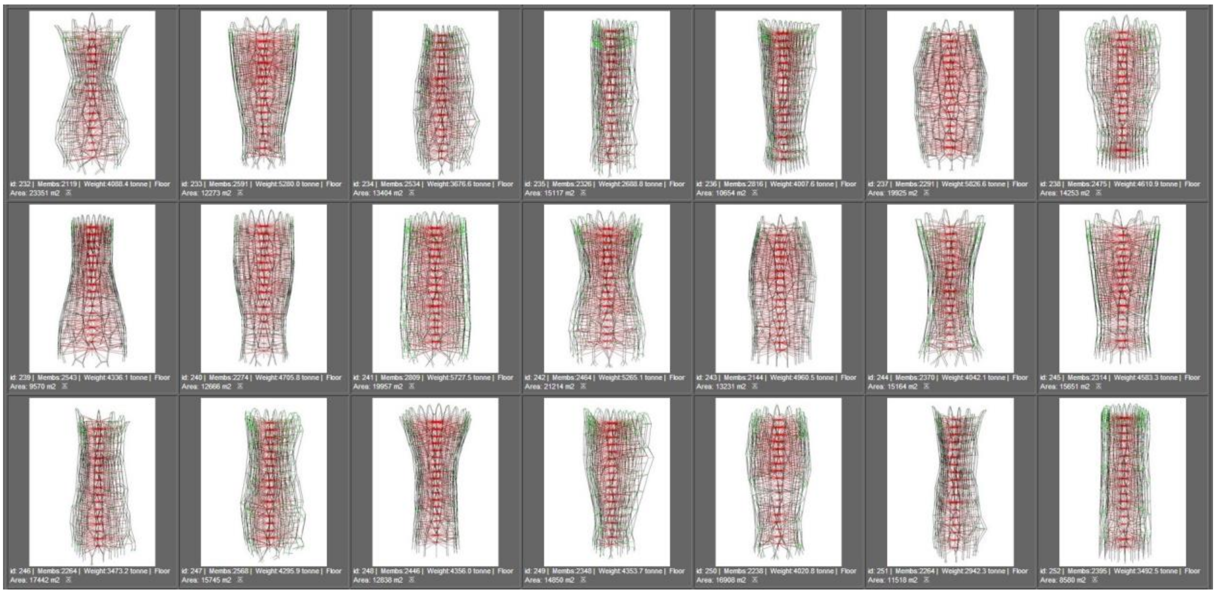

Figure 7: Sample of initial, randomly generated solutions. Total number of randomly generated solutions is about 500 in this research.

Multi-objective exploration is carried out through selective breeding of parents picked from the dynamic populations using multiple fitness criteria like deflection, minimal weight, and maximized floor area. In the case of the structural skin design, as with many design problems, there are conflicting objectives which have to be balanced to find the most desirable solutions. For example, although to reduce gravity loadings the optimal structure tends toward a more slender tower, the lateral seismic loading requires bigger lateral dimensions and double skin thickness which increases member length and consequently increase overall weight.

ParaGen has built in capabilities for graphing Pareto fronts and parallel coordinates graphs for the exploration of multiple objectives. Fig. 8 shows a graph of the Pareto front resulting from the comparison of: first modal frequency vs. total weight. By clicking on any of the plot dots, the tower thumbnails are displayed for comparison. In this way trade-offs can be explored along the Pareto front. In this research 750 solutions were generated through the process of form exploration.

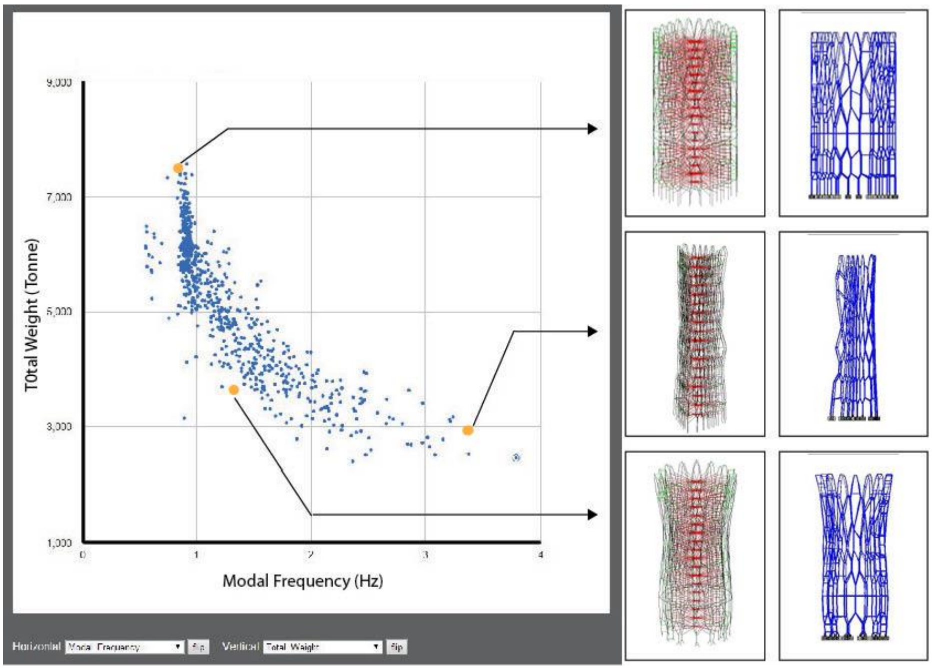

Figure 8: graph of first modal frequency vs. total weight

Fig. 9 shows a graph of two performance values: total weight vs. total floor area. Since the diameter of the tower was allowed to vary, the least weight solutions have a smaller diameter. The solutions with low modal frequencies were also heavier and generally had a necked in second floor which formed a pivot point for the mass of the floors above. Stiffer structures have a cone shaped overall geometry which increases lateral stiffness.

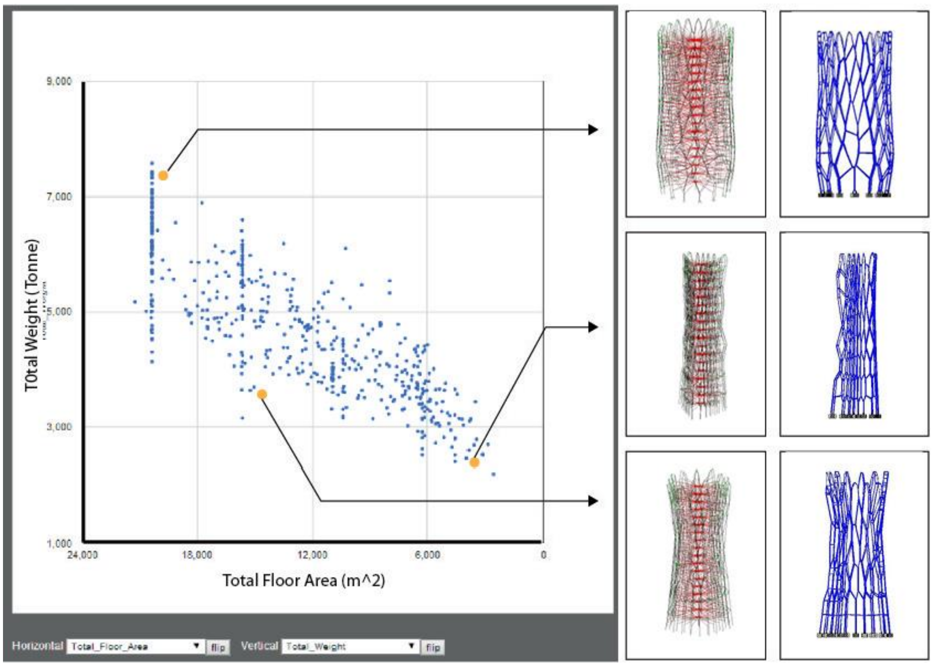

Figure 9: graph of weight vs. floor area

Because all geometric properties as well as the performance values found in the analysis are stored in the solution database and linked to a set of graphic images, exploration of the forms is interactive and controlled through ParaGen's web interface. Any area of the solution space can be described through a bracketing of the geometric and performance values in the menu at the top of the web page. Fig. 10 shows the search control settings and the resulting solution set. By changing the search parameters different areas of the solution space can be made visible.

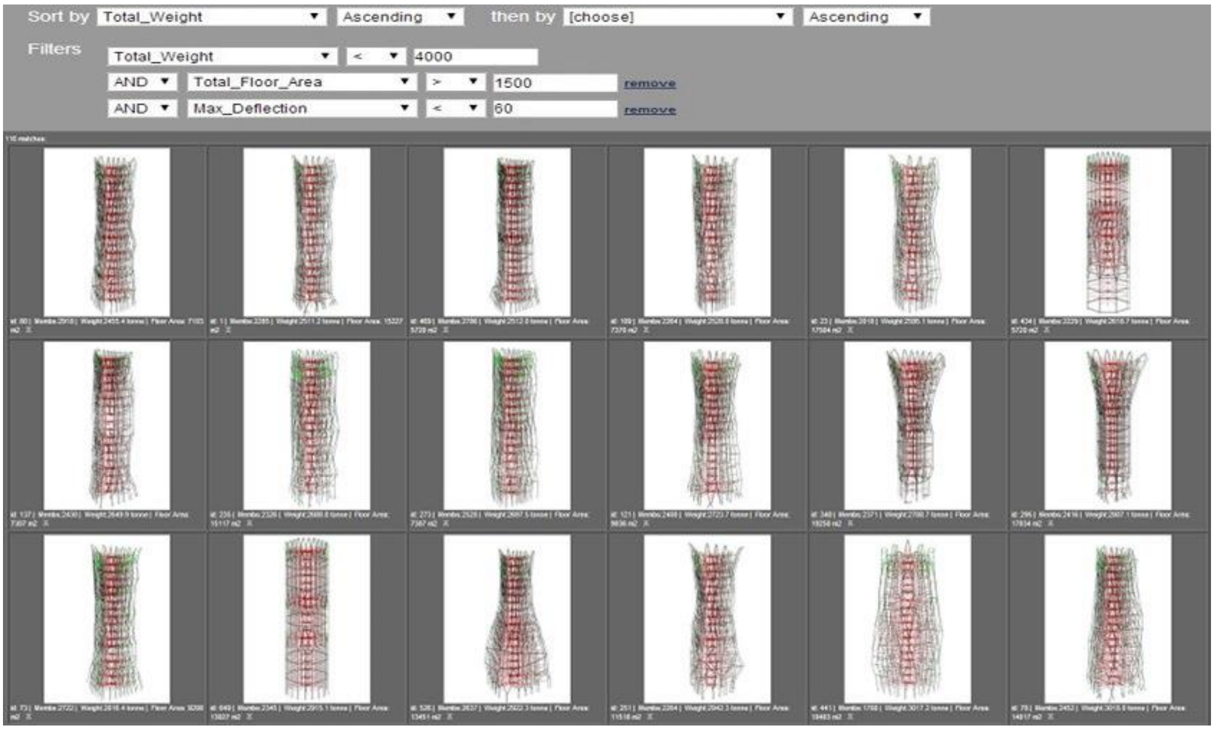

Figure 10: Solutions found using search control setting in ParaGen

6. Effect of double skin thickness on the structural performance

Double skin façade systems can significantly increase the environmental behavior of the building. The contribution of these double layered systems to structural behavior of the skin can be explored if they are designed as a loadbearing system. For this reason one of the generated forms is chosen and regenerated once with one meter double skin thickness and again with three meter thickness. The comparison of the structural behavior shows that with 2% increase in the structural weight the structure has become 8% stiffer in resisting lateral deflection.

7. Interactive design and manual crossover

Using different search setting and filters through the web interface the designer can see a pallet of generated forms based on any desired performance criteria. Moreover, the designer can choose different design solutions and cross them and create a new solution. In this way qualitative aesthetic of the structure can be the selection criteria as well as quantitative structural performance. It was observed that the lighter weight solutions tended to have continuous vertical members rather that more random Voronoi patterns. For reasons of visual aesthetics, the solutions with the more random cell patterns were preferred. In order to explore the possibility of having a more random pattern on one of the lighter weight tower profiles, two solutions were chosen and crossed. The first solution shown in Fig. 11 had the random pattern while the second solution was lighter weight. Crossing the geometric parameters of the two forms, the third form was generated with properties of the first two. (See Fig. 11).

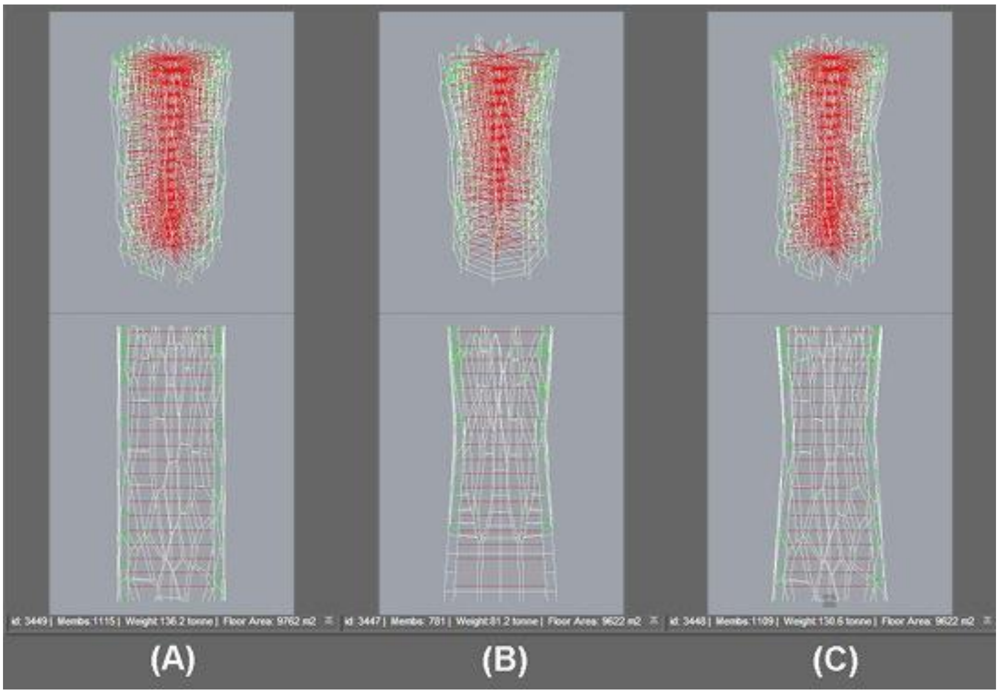

Figure 11. Interactive breeding of geometric parameters. Solutions A and B are the designer selected parents of the child solution C

Parameters	Weight (tonne)	Deflection (cm)	Frequency	Base Shear (tonne)
Regular Voronoi (B)	4723	57	1	518
Random Voronoi (C)	6426	48	1.02	667

Figure 12. A comparison of performance values from the three solutions shown in Fig. 11

In this exploration, the desired visual form was obtained, however the performance was of course affected. Figure 12 shows a comparison of performance values of the orthogonal pattern (B) and the more random Voronoi pattern (C). The solution with the more random Voronoi pattern is 36% heavier with 29% larger base shear. Although perhaps visually more interesting, the more random pattern is less structurally efficient.

8. Discussion and Conclusion

The main purpose of this paper is to illustrate the application of genetic based form finding process in exploration of complex cell morphologies as a load bearing system in double skin façade structures, these biological patterns can produce visually complex forms as well as performative systems. ParaGen successfully integrates the generative form finding process with performance evaluation which enables the designer and engineer to explore and evaluate complex performative forms. The double skin systems explored in this paper are designed as the main load bearing system for the tower structure, more over the double skin façade can be designed based on environmental performances in the same form finding process to reach a more integrative design solutions.

In this example ParaGen combines associative modeling software with finite element analysis software and a genetic algorithm. The parametric model creates the complex morphology of the tower skin based on Voronoi patterns using a small number of parameters. This associative model is very flexible so the GA can be effectively used to explore the design space using the various fitness functions supplied.

In this example the complexity of generated Voronoi forms generated are visually desirable, while at the same time structurally efficient forms are also sought. The flexibility of the parameters in controlling overall geometry through radius of the stories as well as local geometry through resolution of Voronoi patterns makes ParaGen an effective method to explore the innovative forms.

During the multi objective breeding in the final generations based on minimized weight, and maximized floor area, structures with more continuous vertical members, with cone shaped geometry had better performance presumably due to continuous load path and more stable global (see Fig. 10).

Although the initial generation and analysis of populations takes relatively a long time, the subsequent exploration of the solution database created is near instantaneous and certainly interactive. Of course any number of machines can be added to a cluster with the result of faster processing times. All that is required is the availability of the software being used in the generation and analysis phases and an internet connection to access the server and database. As a result the ParaGen method can be used to advantage in exploring complex problems with multiple performance objectives and large geometric variability.

Acknowledgement

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