Tumbling Units: Tectonics of Indeterminate Extension

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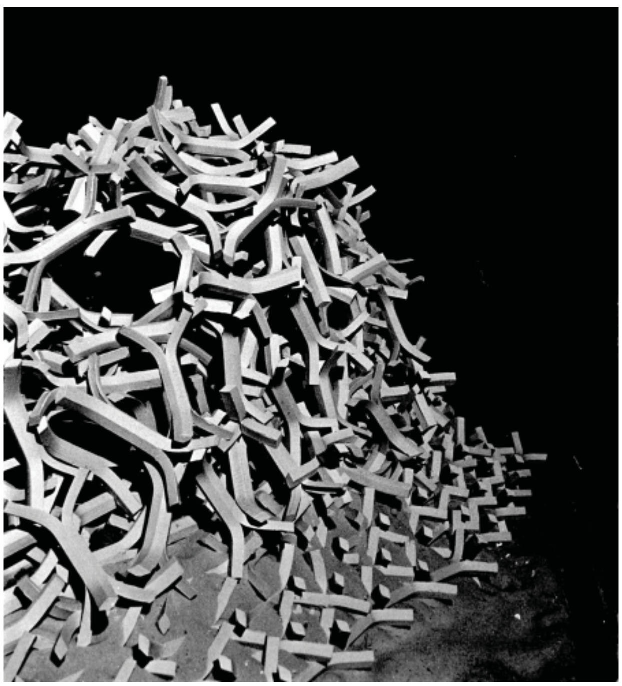

Figure 1. Tumbling Units Canopy (Side View)

INTRODUCTION

The construction of exceedingly complex buildings are the testament to the recent technological advances in the field, namely the precision and the speed of new digital tools made possible by the affordability of sheer computational power.

What happens if we do not have access to such power? In the world of 19th century classical physics, this limitation prompted the emergence of statistical physics, a major paradigm shift. Can we conceive of a complex building system without relying on these computational muscles?

This paper discusses the design and production of friction bound ceramic structural units as a possible building system with indeterminate internal extensions. It also presents the results of a systematic experimentation of their tectonic possibilities as an aggregate system.

COMPLEXITY / PRECISION / EXTENSION

> "The properties of shear-tie are fully embedded within the solid representation. Any dimension can be derived completely and accurately from the solid model, rendering the once necessary dimensional drawings now obsolete."[1]

The shear-tie mentioned above fastens the exterior skin to the frame of a Boeing 777. In the book *refabricating ARCHTECTURE*, Kieran and Timberlake discuss how every component of this airplane is precisely modeled in the virtual environment. In addition to the full description of geometric information, each virtual part is embedded with other design controlling factors such as the physical properties and its life cycle records. A Boeing 777 consists of over one million parts, an object the size of a small building with enormous complexity. Keiran and Timberlake argue that without the technology to predetermine the data in pinpoint accuracy beyond the simple dimensional tolerances, it will not be economically feasible to build such a complex object. They make a convincing case for architecture and construction industries to adopt the technology already fully embraced in automobile and aerospace industries.

Frank Gehry was one of the earliest to do so. In the forward to the book *Iron: ERECTING THE WALT DISNEY CONCERT HALL*, Gehry writes;

> "CATIA also allowed extremely complicated steel to go together on the site without the kind of problems that happen on similar sized buildings. Due to the consistency of information and the precision of the calculations, every element tied back to an origin. When an Ironworker was on the scaffolding, he could get someone to survey him a point and know he was within an eighth of an inch."[2]

For Gehry, it was an absolute necessity to adopt the technology in order to realize his complex sculptural forms. He goes on to speculate that if it was not for CATIA, the three dimensional surface modeling program developed for the aerospace industry, it would have taken him decades to meet the computational requirements alone for the design of the Walt Disney Concert Hall.

A building system is literally and metaphorically an extension[3] of a vast number of similar elements. In general, more complex the building, more accuracy is expected in extending the elements both in design and in execution to make them economically feasible. The construction of an exceedingly complex building such as the Walt Disney Hall is testament to the recent technological advances in the field, namely the precision and the speed made possible by the new digital tools.

COMPUTATIONAL MUSCLES

If the future of architecture is dependent upon these new digital tools, what makes these tools possible?

> "The complexity for minimum component costs has increased at a rate of roughly a factor of two per year. Certainly over the short term this rate can be expected to continue, if not to increase. Over the longer term, the rate of increase is a bit more uncertain, although there is no reason to believe it will not remain nearly constant for at least 10 years. That means by 1975, the number of components per integrated circuit for minimum cost will be 65,000. I believe that such a large circuit can be built on a single wafer."[4]

In 1965, Gordon Moore, the future co-founder of Intel Corporation, published the now famous article; *Cramming more components onto integrated circuits* on an obscure electronic trade magazine, Electronics. He predicted that the number of transistors economically placed on an integrated circuit will increase exponentially, doubling approximately every two years as mentioned in the above quote. This notion has since been widely embraced by the industry as "Moore's Law." The key in reading the article is his careful attention to the impact of such rapid technological advance in the context of economy. If we assume that the computational power is proportional to the number of transistors on the single chip, we will see exponential growth in the power for the same price year by year.

Gordon writes, "Computers will be more powerful, and will be organized in completely different ways. Machines similar to those in existence today will be built at lower costs and with faster turn-around."[5] Many future products he had mentioned in the article did come to a fruition - Electronic wristwatches, home computers, automatic controls for automobiles, personal portable communications equipment to name a few. The availability of the ubiquitous, increasingly powerful computing and its effect on the way of life seems to echo the technological optimism of the era.

Patrick P. Gelsinger, the current Intel Corp. senior president, confirmed that the performance/dollar ratio of computers has increased by a factor of over one million in the past 30 years, in line with the Moore's Law.[6]

We are surrounded by computers. Our future advancement seems to rely ever more on the continuation of this trend, the exponential increase of the affordable computational muscles. This is precisely what makes these new digital tools possible and increasingly viable in the field of architecture.

DETERMINACY / INDETERMINACY

This reliance on computational muscles, however, was not the choice late 19th century classical physicists had when they were studying particle motions on a molecular level. Instead, this limitation gave birth to statistical physics, a paradigm shift which lead to the eventual emergence of quantum mechanics.

> "It is true classically that if we knew the position and the velocity of every particle in the world, or in a box of gas, we could predict exactly what would happen. And therefore the classical world is deterministic."[7]

Classical mechanics are known to be a simple and beautiful way to describe the relative motion of macroscopic objects. In principal, any problem in mechanics can be solved based on Newton's second Law of Motion. This is indeed true when dealing with one or two bodies in motion. However, it becomes exponentially difficult to solve when the number of bodies involved are greater than two. The famous three-body problem, two planet bodies rotating around a sun for example, challenged the power of human analysis for ages. Such Problems cannot be solved in elegant, analytical mathematics with the deterministic accuracy. It is necessary to resort in approximations through heavy numerical calculations.

Thus, when it came to dealing with a molecular level description of the behavior of a gas, the 19th century scientists had to come to terms with the task of numerical calculation for every single molecule. Without a massive computational power at their disposal, this was physically impossible. Instead, they discovered a ingenious work-around to the seemingly insurmountable obstacle in the form of "probability." Statistical mechanics was born. Statistically dealing with large number of bodies resulted in indeterminacy. Looking back, accepting the indeterminacy as part of the nature, forced an enormous paradigm shift in the world of physics. This shift, ignited by the works of Maxwell and Boltzmann, eventually lead the second revolution in the field, paving the way to the development of quantum mechanics by such giants as Einstein, Heisenberg and Bohr in the early 20th Century.

TUMBLING UNITS

Fueled by the proliferation of sophisticated computer simulations, it is now tantalizingly close to predict exactly what would happen in the box of gas, molecule by molecule. The interest in the classical physics problems have been reinvigorated and reexamined closely in the recently established field of computational physics.

The affordability of the computational muscles has also impacted the field of architecture, perhaps, a little too soon. It is analogous to bestowing massive computational power to the 19th century scientists. It is easy to speculate that the availability of such power may have hindered the game altering development of statistical mechanics.

The current technological obsession in architecture is one-dimensional. As it is evident in the Gehry's earlier remarks, the advances are measured in terms of speed, accuracy and in turn, economy. With the deterministic precision made possible by inexpensive computational power, we can design and build a complex building cheaper in a much shorter time. Kerian and Timberlake merely reaffirm this point through the idea of prefabrication and mass customization.

Is it possible to conceive an ingenious work around in the field of architecture, equivalent to the introduction of probability to the molecular behavior of gas? Can we conceive a building method that does not rely on precision in an ordinary sense? Is it possible to form a building system with an indeterminate system? What will be the tectonic implications? The Tumbling Units[8] were conceived in an attempt to address these questions. The friction bound ceramic structural units were designed and fabricated as a possible building system with indeterminate internal extensions.

BASIC GEOMETRY

The basic geometry of the unit is conceived as a hybrid of (2) tetrahedrons attached at a vertex with 30 degrees offset rotation, composing a dumbbell shape. The prongs at the both ends of the main axis function as an indeterminate joint condition to cling and/or stack to one another. The member connecting the tetrahedrons gives the capacity to span

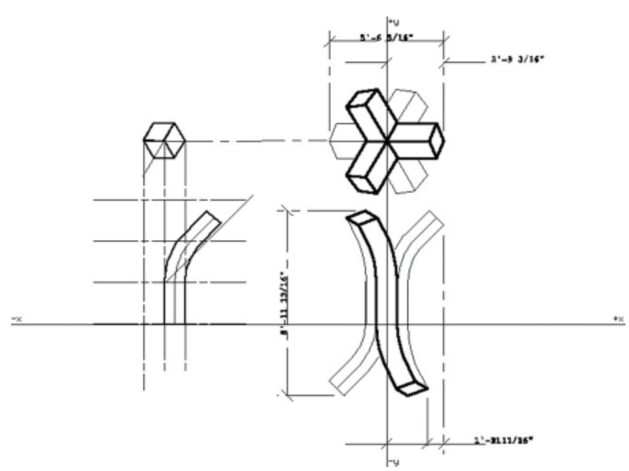

Figure 2. Orthographic Drawings

The actual form of the units depends on the material and the production methods. Several alternative designs were investigated and evaluated based on the ease of production, rigidity, density (scale/weight) and esthetic concerns (form/materiality). This design based on ceramic stoneware proved to be the most desirable, allowing the rigid continuous forming of complex geometry with substantial material quality.

FABRICATION

There are a number of resistance factors to contend with in fabricating elements of multiplicity. The design parameters were established so that it is feasible for one person to economically produce (1000) units in (30) days using a single (5) c.f. electric kiln.

The property of wet clay is typically characterized as plastic. However, this is not necessarily an accurate description. Clay exhibits an elastic property when the moisture content is relatively low. Its property swings from plastic to elastic depending on the moisture content. The fabrication method exploits this subtle variation of stoneware to the fullest extent.

The pre-mixed stoneware was extruded through a custom fabricated hexagonal die in approximately (3’) length and left to dry for about (45) minutes to the desired stiffness. The strand of extruded clay was then cut to length. Subsequently, both ends were manually split into (3) prongs and spread into the approximate shape.

The weight and the size of each unit were the critical controlling factors in the production tolerance. It was necessary to carefully balance the drying time required to meet the production schedule against the changing elasticity of the clay prior to firing. The spread of the prong depended on the weight of the unit and the elasticity of the clay. The units were air-dried approximately (2) hours at room temperature in an upright position, the sides flipped and dried for additional (3)-(3 1/2) hours. The timing of flipping was also crucial to balance the top and bottom spreads since the unrestricted prongs on top began to close in as the clay dries.

Note how the tolerance of form depends on the material’s internal response to the gravitational forces, not through a direct artificial manipulation. The external controls imposed are the initial condition and the duration. The material tendencies will take care of the rest. The air-dried units were then loaded in the kiln, fired at cone (2) and left to cool overnight. At the end, over (600) units were produced. One of the unexpected formal outcomes was the unique inflecting surface observed in the unit.

TECTONICS OF AN AGGREGATE SYSTEM

As the production progressed, the behaviors in a small number of units were systemically catalogued. Simultaneously, a larger number of units were employed to explore the range of tectonic possibilities as an aggregate.

Based on observation, a simple extension offers (3) distinct directional freedom without considering the specificity of the exact angle in a pair of units. Assume the average number of units consisting an extension node is (3) units for an aggregate of (100) units total.

Possible extension combination per node:

3^3 = 27

Number of nodes in an aggregate of (100): ${}_{100}C_{3}$ x (1+1/3+1/3+1/3) = 323400[9]

Then, the possible combination (state) of the aggregate reflecting the directional freedom at the nodes: 323400 x 3^3 = 8731800, a rather large sum. The number tells us the magnitude of the possible configuration of the whole aggregate, a step forward towards quantifying the tectonic characteristics using statistics.

Let us consider what can be quantified as tectonic characteristics of this aggregate. One of the obvious parameters is the number of units consisting each extension nodes. In the previous analysis, we simply assumed the average condition. The further observations reveal that the number can vary somewhere between (2-5). It is also clear that these are not randomly assigned numbers. It is the result of an equilibrium reached against the conglomeration of various geometrical, gravitational and contextual influences that can be held constant in the macro scale. Thus, by conducting a large number of empirical experiments, it is possible to statistically establish a distribution pattern against the overall state of the aggregate system.

In turn, through the numerically established distribution pattern, it is possible to predict the probability of observing (x) number of extension nodes constituted by (y) number of units in an aggregate system with (z) number of total units and so on. A role equivalent of the Maxwell-Boltzmann's distribution in the statistical mechanics.

Through the introduction of statistics, it is conceivable to establish a "most probable" tectonic characteristic of an indeterminately complex system.

CONSTRUCTION SEQUENCE OF AN INDETERMINATE SYSTEM

Human judgment involved in the extension of the units is one of the controlling, yet less consistent, macroscopic factors in the earlier tectonic studies. A sensory and motor skill level of the human hand depends on the individual's talent and training. Further, it is impossible to replicate the kind of delicate balancing act human hands are capable of in the scale of building construction.

The skilled labor/judgment issue is a common topic in building construction. In fact, this is one of the reasons why this kind of precision, the ability to virtually map every building component with accuracy, is sought after by such architects as Kiran/Temberlake and Frank Gehry as discussed in the earlier examples. It is an attempt to eliminate the discrepancy between the design and execution by identifying every building part and correlating them one to one in the model. The thinking is that by minimizing the unknown, little skilled onsite judgments will be required. The ultimate goal of such a system is for the components to go together in a predetermined, singular manner.

An alternative approach in deploying the units is speculated and tested in the following example. A mound of silica sand is formed inside an elevated (3'x3') plywood box. The bottom of the box is designed to evenly drain the sand, sloping to the

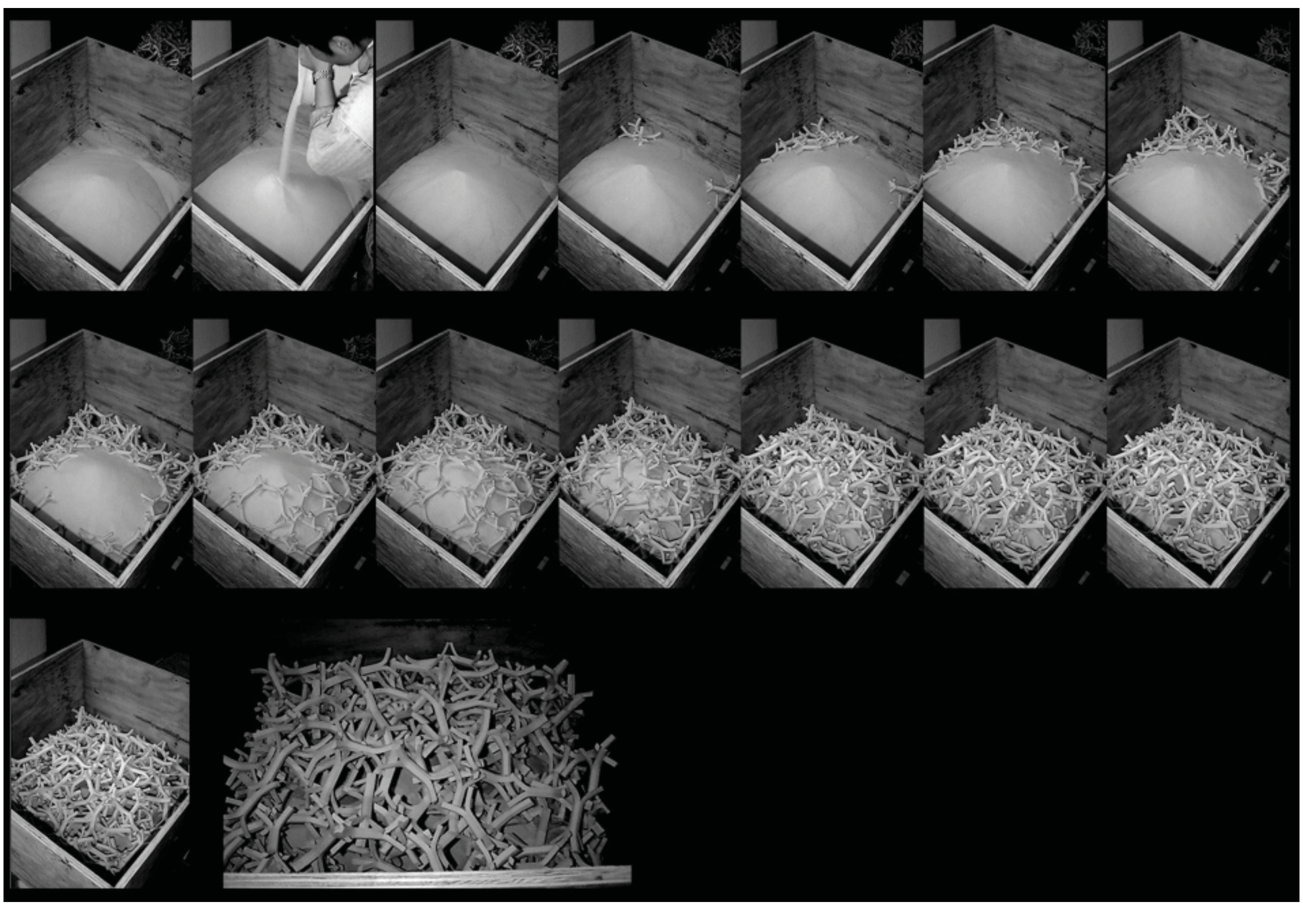

Figure 3. Tumbling Units, Construction Sequence via Silica-sand Formwork

(1”x1”) center opening. The units were first placed along the edge of the box in higher density to accommodate the anticipated lateral and vertical force transferring into the box. Then the remaining area is loosely filled in with layers. General attention was paid only to the direction of the units to lie evenly distributed against the slope of the sand. As it was drained, the units fell into place and locked into each other seeking a gravitational equilibrium without any external interventions. This resulted in a formation of a shallow dome, spanning across the plywood box.

In actual building scale construction, slightly different tactics may be employed substituting the mound of sand with inflatable formwork. Once the elements are roughly placed in position by crane, the formwork is deflated slowly, inducing a similar effect to draining the sand. In this scenario, the skilled onsite judgments are also reduced, however, without relying on computational muscles and the precision necessary for a predetermined system.

INSTALLATIONS

Over and above the basic human need for shelter, architecture aims to evoke an emotional and intellectual response. Acrobatic forms are often justified as one of the elements of the surprise. However, there are other phenomenal qualities such as materiality, texture, light, shade, time, sequence, scale, proportion and spatial, structural order. Various aforementioned experiments have culminated in temporary installations for (2) exhibitions exploring these qualities beyond the acrobatic form. All (600 +/-) units were used for both occasions.

In the first exhibition, the Graduate Degree Exhibition at Cranbrook Art Museum, Bloomfield Hills, Michigan, the units were configured into a self-supporting oblong dome in the size of (HWD: 3’x4’x3’). Exploring the tectonics of spatial/structural order was of prime interest. Attention was paid to the gradual transition from the more ordered configuration at the foundation to more random configu-

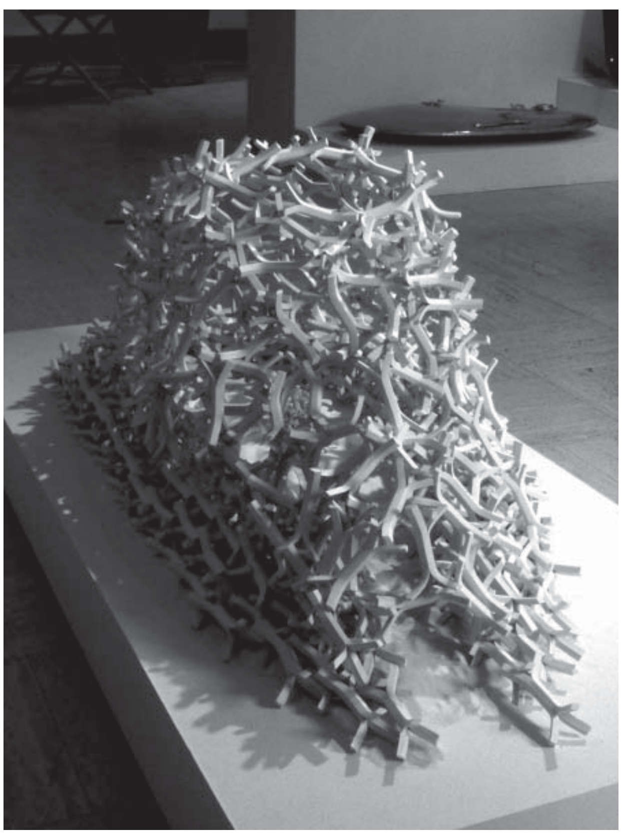

Figure 4. Tumbling Units Canopy

Figure 5. Tumbling Units Light Filter

rations at the top. A layer of silica sand stabilized the foundation by filling in the gap, increasing the friction against the platform for lateral support. The viewers were fascinated by the contrasting qualities of the dome. The surprising stability as an assembly despite the delicate qualities of the ceramic units in friction-bound. The museum guards have informed me that there were numerous attempts to touch and to dislodge the units during the (2) weeks of exhibition in May 1997.

In the second exhibition, the CoA Faculty Exhibition at Louise Hopkins Underwood Center for the Arts in Lubbock, Texas, the units were stacked against a large storefront window to take advantage of the given context. Exploring the phenomenal qualities of light/shade and scale/proportion were of the prime interest.

CONCLUSION

The reality of current building practice is to execute a complex building efficiently with minimum risks. The technology and its computational muscles are almost exclusively used for this purpose. The Tumbling Units, the exploration of indeterminate extensions aims to provoke the deeply entrenched architectural practice through questioning the obvious and the rational in a most fundamental way.

ENDNOTES

1. Stephan Kieran, James Timberlake, *refabricating ARCHTECTURE*, McGraw-Hill, New York, 2004, p.61

2. Gil Garcetti, Forward by Frank O. Gehry, *Iron: ERECTING THE WALT DISNEY CONCERT HALL*, Balcony Press, Los Angeles, 2002, p.8.

3. extension: almost interchangeable with a joint, however the emphasis is on the relationship of one part to another, not the space in between.

4. Gordon E. Moore, *Cramming more components onto integrated circuits*, Electronics, Volume 38, McGraw-Hill, New York, 1965

5. Moore

6. Gelsinger, PP, Gargini, P A, Parker, G H, & YU A Y C, 1989, *'Microprocessors circa 2000'*, IEEE Spectrum, Vol. 26 No. 10, October, pp 43-47.

7. Richard P. Feynman, Robert B. Leighton, Matthew Sands, *The Feynman Lectures on Physics*, Addison-Wesley Publishing Company Inc., Reading, Massachusetts, P.38-39.

8. The units were designed and fabricated as the author's M.ARCH II thesis project at Cranbrook Academy of Art in 1996-97. Advisors: Dan Hoffman and Peter Lynch.

9. "${}_nC_k$" stands for combination: *n* is the number of objects from which you can choose and *k* is the number to be chosen.