Heavy Design
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Abstract
Digital tools in architecture have a powerful capability that we have only begun to explore; the questions to ask of them are perhaps not what they can do but what should we use them for? To date, much of the work done in the area of computational design has been used as elaborate patterning - some have called it 'ornament'. The significance of this ornament is not only pleasure but in its use of digital patterns to represent our current complex and digital age. This representation in itself is not problematic; however, what is problematic is the lack of other meaningful uses of the digital form-generating tools and their distance from a culture of making. The main failing of our use of digital design (algorithmic or not) in architecture to this point is its inability to translate smoothly from the digital world to the physical world. The main reasons for this difficulty in translation are gravity and inherent material properties. Working with gravity and its physical implications is generally considered the role of the structural engineer; as such, engineers have generally created digital tools in this area. The engineer’s methodology analyses a structure based on complex structural analysis programming but in order to do this, a detailed description of the structure must already exist. This is not useful in preliminary stages of design. However, the generation of architecture within an environment, which already includes structural principles, may bring us one step closer to this transition of virtual to physical by including gravity in architectural generation while not diminishing the creative form-generating process. An approach has been proposed which responds with a concept of 'heavy design'. This type of approach incorporates logics from other disciplines, primarily structural engineering, to inform design. The design process incorporates the structural behavior of a system into the architectural model. Engineering offers a mathematical interpretation of the physical world and this is inherently suited to algorithmic design because it is already in equation form. It can thus be programmed into the architectural form generational software. The variables used in the equations become the variables within the architectural design and this inherently brings the natural physical laws to the architecture through a numerical, algorithmic method. The design produced is not a singular answer but rather a responsive vocabulary of a structural system, which is then employed in design in differing conditions. The architecture produced is both function and ornament, having cultural interpretation but carrying out many engineering tasks: a true parametric architecture.
I. THE CONTEXT FOR HEAVY

1.1. ‘Deep’ discussions

The question implicit in much of the criticism of parametrics today is: is it only ornament? We can approach the discussion with a gradient from only ornament to only function. Where ornament has been critiqued, beginning in 1908 with Adolf Loos’ famous manifesto “Ornament and Crime,” there is also widespread skepticism of a purely ‘functional’ design. Functionality, as we discuss it in architecture, typically favors efficiency within a narrowly defined field; functionality is seen as being closer to an engineering approach and was primarily defined by the modernist movement as a counterpoint to decoration. In “Ornament and Crime” Loos describes ornament as a necessity of the primitive man, arguing that lack of decoration is the sign of a progressive and advanced culture [1]. Kolarevic has argued for a more Semperian approach [2] which claims that architecture is in itself an ‘ornamental activity’ and that it has purpose in its presence and appearance, giving scale and texture and imbuing cultural significance through symbolism and the representation of cultural and social content. This argument provides a ‘reason’ for ornament with the reason itself referring to the desire for functionality brought forward by the Modernists. However, there is a desire in parametric design to move along the gradation from decorative towards functional, and many projects have eroded the purity of parametrics as ornament alone and ventured into the realm of functional. For example, the Herzog & de Meuron De Young Museum in San Francisco integrates 7000 copper panels into its design, each of which has a unique half-tone cut out and embossing patterns abstracted from images of surrounding tree canopies; the function of these panels is to hide the building’s ventilation system and to diffuse exterior light going into the galleries. This design is somewhat functional but still incorporates strong elements from the ornament side.

Perhaps the strongest driver for a desire for parametrics to move away from ornament is the challenge that it does not respond to a culture of making, and that it cannot be easily made and does not consider issues of gravity and materiality. These shortcomings have been challenged on multiple fronts and are defined in a new movement that has been termed “New Structuralism” [3] which has architects functioning much more as material practitioners than in the past. The consideration of the material, structure and process of making is being recognized as becoming a major impetus in architectural thought. Projects such as those suggested by the New Structuralists subvert the typical order of architecture where the architect conceptualizes a project and then an engineer materializes it. Within New Structuralism practices, the engineer works with the architect at the conceptual point of the project, bringing materiality into the discussion from the onset. The methodology discussed in this paper is not so much that the
architect works with the engineer at the onset, but that the architect works with structural concepts from the onset, thereby materializing an architecture based on structural logics.

To elaborate further on current discussion about the new movement, and specifically regarding structure, the idea of ‘deep decoration’ has been introduced [4]. Deep decoration is a structural-based theory that “fuses culture and technology” [5] and produces an architecture which incorporates structure into its generated form both completely and holistically. The structure functions fully as a primary architectural element. The approach outlined in this paper corresponds to an idea of ‘deep decoration’ and can be considered part of the New Structuralism; however, this approach is more integrated with the architectural generation of concepts, and rests within the scope of the architect. It intends to produce a vocabulary, not a finished form.

1.2. The role of biological thinking

Other approaches embedded in ‘heavy design’ involve the concept of biomimetics. Discussed widely by Michael Weinstock and colleagues at the Architectural Association School of Architecture, biomimetics abstracts the design principles of biological systems and applies them to the design of buildings and artifacts. Weinstock points out that

[B]iological systems are self assembled, using mainly weak materials to make strong structures, and their dynamic responses and properties are very different to the classical engineering of manmade structures … Evolutionary biology has utilized redundancy as a deep strategy implemented at many levels, in multiple and complex hierarchical material arrangements and differentiation to achieve robust and stable structures, whereas engineering has traditionally sought the minimum of materials, simplicity of structural organization, and the standardization of components and members.[6]

This idea of redundancy allows a complexity in the generation of forms. Using multiple members rather than a singular load path may also allow the flexibility to adapt to different loading cases. The form of the design may vary from part to part, depending on the specific loading conditions or spanning configuration the structure encounters. While the structure may indeed by conventional engineering standards be more ‘inefficient’, it may have other benefits to its design which render it useful socially, culturally, or for other architectural means – for example, a structure for the curtain wall lateral forces.
As an example, the algorithm used for the project Heavy Wall [Figure 1]
is a self-arranging system, similar to subatomic particles, where each column
element is attracted to each other by a squared mathematical relationship
allowing a system where elements connect in a three-dimensional space; it
can be likened to a magnetic attraction. The goal of the attraction is to
allow the columns to touch in order to reduce the effective length of the
columnar elements. Through the process of the wall optimization,
modification of the elements of the wall takes place, at first changing wildly
and then slowly twitching as the algorithm converges. The algorithm used to
create this design generates a hundred structures, each unique, and then
organically evolves the structure by combining portions of the walls whose
structural configurations better suit the application. The iteration of this
process continues until the solution converges. The architectural intent is to
introduce multiplicity into the structure, creating many load paths while
using smaller material elements. The result is a structure, somewhere on the
continuum between wall and column, which is permeable and expressive.
The algorithm can also be applied to a columnar configuration instead of to
a permeable wall configuration (say, for a curtain wall exterior supporting
structure) by adjusting to its spatial requirements. The number of elements
can be varied depending on the load capacity required - i.e. a larger
tributary area uses more structural members.
1.3. Further notes on gravity

Looking at gravity as a natural law, Greg Lynn points out two different perspectives as proposed by Rene Descartes and Gottfried Wilhelm Leibniz [7]. Descartes proposed a gravity of stasis: a system where time and force are eliminated from the equation which produces discreteness, timelessness, and fixity - a single discrete point place in space. On the other hand, if we look at gravity as a more complex issue, as proposed by Leibniz, it is a mutual attraction generated by two bodies in motion: there is no stasis, only stability. This can change our view of structures, as when you adjust one element of a complex structure, other elements will adjust in order to come again to equilibrium. Vectors then begin to act and we can see them in many places. Looking at splines, Lynn points out that they are vectors defined with direction; they are “suspended from lines with hanging weights, similar to the geometry of the catenoid curve. Yet unlike a catenoid curve, a spline can accommodate weights and gravities directed in free space.” [8]

As is the case with a spline, in complex geometries in a structure, a single change in a vertex will affect multiple regions; similar to a spline, this effect of a disruption in the system will ripple throughout the structure but at a certain point its effect will eventually die out. This effect can, for example, be seen in the design of a multi-span bridge structure for the varying construction gravity loads: as concrete is poured in one span, the effect of the loading of the wet concrete causes haunching in the other spans but the effect of this loading decreases as the distance from the pour increases and then dies out a few spans away. Similarly, it can be seen in the loading and unloading effects of spans in multi-span steel building structures. The use of various lenses to understand gravity allows the architect to approach the design in new ways, realizing that a structure is a body in equilibrium whose forces are always dynamically readjusting.

1.4. Implied mass customization of structure

The use of mass customization is also part of the context for this methodology and it allows for the structural gymnastics required for a constantly varying structure. Variation can be constructed easily when materiality is taken into account within the original modules, which are being considered. For example, cutting multiple steel plates with varying profiles is not at all problematic in a steel shop since all the cutting is based on CAD drawings in any case. Within the process, the materiality must be embedded in order to analyze the structure. Structural analysis software, rather than architectural software, constrains materiality somewhat, thus ensuring a consideration of easily fabricated but highly customized structural elements. Material connections are also key and are required to be defined in the analysis process; again, this will require consideration from the designer at the initial design stage.
2. INCORPORATING HEAVY

2.1. Freeing the design process: generating vocabularies

Typical methodologies for incorporation of parametrics into a design process have an embedded challenge in that the designer must deterministically program coding. This process is not experimental; it is either a matter of optimizing outcomes based on multiple parameters or generating multiple results and then selecting from these results. In both cases, sometimes-unforeseen results occur; this can lead to interesting design outcomes but the programming is still deterministic in some form. This raises the question of how to incorporate parametrics into design. The methodology that is illustrated in this paper takes on parametrics at an early stage in the process but it is meant to select attributes of a design requirement and then manipulate these attributes to generate a vocabulary to be used architecturally. To develop a vocabulary is perhaps one of the strongest attributes of a parametric process: variation can be used to enhance design and the design can flex in multiple ways to respond to the changing conditions. In this case, the design requirement is a functioning structure and the attributes are the parameters of the structure that deal with gravity. The vocabulary developed can then be manipulated (also parametrically) and subsequently applied to the design requirements as the program/site/span etc. change. The structure is then responding to the architectural criteria – generating form, expressing variation, and performing functionally.

▶ Figure 3: Structural analysis of several variations of a roof structure spanning element.
2.2. Translations of gravity

As we seek to solve a problem in architecture, we can look to natural solutions as well as to natural laws. As discussed, natural solutions may not be a rule-based environment which offers only one solution, but may instead allow a variation in structure configuration or even the fibre configuration of a structure in order to adjust to a loading condition. While this works in nature, one can see how it could work within different configurations of architecture: different plan configurations, sun angles, spans, and so on.

Nevertheless, how to choose what to vary? Natural laws are mathematical interpretations of our environment through physics and
applied in engineering. We can therefore take natural laws and mine their structural principles and equations for concepts with which to work. If we are looking for a methodology by which to support a heavy load with a structural system that seems lighter, as in the Heavy Wall project, we then question the vertical load bearing element: column buckling is a phenomenon which governs the design of vertical load bearing elements in architectural form. To look at the structural equation that governs buckling:

\[ P_{cr} = \frac{\pi^2 E I}{L^2} \]

where \( P_{cr} \) is the critical loading for the column, \( E \) is the modulus of elasticity, \( I \) is the moment of inertia of the cross section of the column and \( L \) is the effective length of the column. From this, we can see that the major factors affecting buckling are \( E, I \) and \( L \), but \( L \) is squared so it is much more significant in the column’s behavior. \( L \) relates to the ‘unbraced length’: a braced column will have a higher load bearing capacity than an unbraced column. This leads us to think that we could play with the effective length and so the algorithm could be designed to minimize effective length (see Figures 1 & 2).

Looking at a steel spanning element in a frame type form, the maximum deflection for a fixed beam at centre span is:

\[ \Delta = \frac{wL^3}{384EI} \]

where \( \Delta \) is deflection, \( w \) is the uniform loading, \( L \) is the span, \( E \) is the modulus of elasticity (a material property) and \( I \) is the moment of inertia (a sectional property). This tells us that as variables to play with in our algorithm, the most effective will be span; if we look further into \( I \), which is dependent on the section used, the depth will also be a cube relationship, leading to the depth of structure also playing a critical role. The designs in Figures 6 through 8 show a structural element with a design flexibility and analysis that are based on this design approach. End conditions in this example are also relevant. A moment frame behavior will change the material location throughout the structure as compared to a beam resting on columns and this can provide another set of structures – adding another variation of structure to our vocabulary.

A discussion of beam bending, which is related to deflection in its critical variables, has resulted in projects such as those in Figures 3 through 5.
Figure 6: Sliders showing variables relating to structural equations used on a structure.

Figure 7: Generated variations based on slider manipulations and design algorithm.
Looking to a discussion of shear in slabs, column locations are locations of maximum shear. Looking at the equation for shear in a beam (a simplified analysis compared to a slab but similar in principle):

\[ V = \frac{wL}{2} \]

where \( V \) is the shear in the beam, \( w \) is a uniform load, and \( L \) is the span, we can see that the equation has variables relating to span and loading. Column capitals and drop panels are typically used to mitigate areas of high shear in slabs near columns by simply adding material. Larger spans with larger tributary areas have higher loading and need larger columns but they also have increased shear near the columns, likely requiring drop panels, as the slab depth is insufficient. The variables to play with, then, are span, slab depth, and column and capital widths. The example illustrated in Figures 9, 10 and 11 shows a structural arrangement responding to slab stresses and their structural requirements. Modifications and variations in the slab thickness also respond to column spacing. In Figure 9 we can see a pretest with the increased stresses in the slab in areas with column aggregations. This visually demonstrates the stress distributions around a column. To deal with this phenomenon and different programmatic conditions, a variety of column spacings is required, in the first instance generated by an attractor.

Figure 8: Structural analysis on options to evaluate behavior of form v. generated options.
point giving a pattern which shows variation in column spacings radially. To respond to this variation in spacings and its resulting varying tributary areas, a relative increase in column size and capital width is proposed. The result is then applied programmatically (Figure 11). Column shapes are also a potential area for analysis but were not pursued in this demonstration project.

3. EVALUATIVE FEED BACK LOOPS

3.1 Heavy Performance

The criteria for structural performance are measurable and relatively well defined using a quantitative engineering methodology; the end goal is to use minimum material to carry the load required. It can also be considered that one optimizes the load-carrying capacity of the member by modifying the orientation of internal structure, for example, which holds primarily if you have an anisotropic material. To use the minimum material, one can apply the ‘axiom of uniform stress’. The ‘axiom of uniform stress’ is what tells us that the stress will try to equalize and to use material more efficiently. If you have a non-uniform stress on a structure with a constant material and section, then one part of the structure is overstressed or some parts are
understressed, i.e. material is being wasted. Use first name of author if you have it Mattheck looks from an engineering standpoint at nature’s methodologies of adapting to loading:

Almost everything in living nature is in tough competition for energy and living space and only the best designs of high reliability and minimum consumption of material and energy can survive. Therefore, the principle of lightweight and fatigue resistant design is found in nearly every load bearing natural construction. It is realized by a uniform stress distribution at least at the surface of the structures. [9]

Further, Mattheck describes that evolution can take part in either one of two ways: trial and error, or adaptive growth. With trial and error, generation after generation is produced and the strong survive; this allows
those who are better designed to be propagated and the less well-designed to be discontinued. The eagle talon, for example, evolved by this methodology. The other type of evolution is that of adaptive growth. Tree and bone are adaptive growth mechanisms: they put material where it has stress as time goes by and over one lifespan adjustments are made to adapt to differing stress conditions. Both structures are being adapted to perform better and both are applicable to algorithmic methods in generating and refining architectural form.

The aim behind the testing of the found forms within the structural analysis software is to optimize the structure by equalizing the stresses within it, assuming the structure is a consistent material, and taking the material to a comfortable working zone, but not outside its limits under full loading. The idea is that the form and its relationships can be calibrated and refined by the use of iteration to a structural analysis program. This provides testing criteria for algorithmic modification. An iterative process can then take place whereby changing the variables in the architectural algorithm makes modifications to the structure; the structure is then tested for this change. This can repeat until a relatively uniform stress distribution is achieved. Variations to the broader structural configuration can then be made, such as changes in spans, density of members, support spacings or condition, or combinations thereof, and this will result in a series of structures and configurations, which can be applied, as the designer requires.

Figure 12: Structural analysis to test the design: looking for uniform stresses within the allowable range of the material.
3.2. Architectural Performance

While evaluating the structural performance based on its structural behavior requires some time for iterations and is quantifiable, many other design quality issues are more conventional architectural decisions that are made by the architect. The advantage of parametrics in the process is that the design can be altered in the parametric software ‘live’ and multiple options can be seen by the architect as the slider is adjusted. Issues such as entrances, relationships to site and scale of the body in relation to the structural elements are still very much up to the judgment of the architect and are embedded into the programming and the decisions that are made throughout the design process. These concerns may inform the ‘vocabulary’ of what is developed – for example, a smaller scale and smaller span structure may be desired where there is an entrance or a more intimate area and so this kind of structure may become part of the range of options. This is standard architectural judgment and is intended to play heavy-handed into the design methodology; but ultimately, which elements of the vocabulary are used where is a highly architectural decision. The parametrics and evaluation can inform those decisions but the decisions still rest in the hands of the designer. Parametrics help provide faster iterations between options and to fine-tune the design – in this case, the parametrics have additional constraints on them due to the structural behaviour but there is still a broad range of decisions and options within the process.

The other factor to be noted in performance is that often there are multiple ways of adjusting a structure for performance because there is more than one variable in an equation. If a designer is unhappy with the outcome of the modification of one of the variables, another of the variables can be chosen to play with. If, however, too many variables become incorporated, then it is difficult to assess the performance as too many elements are varying and the structural behaviour will be more difficult to fine-tune. In the methodology, as the structure is fine-tuned, it is helpful if all variables are held still except one and the design fine-tuned variable by variable. The decisions on architectural matters can then inform which variables are constant and which change – again giving maximum design freedom to the architect. In general, the methodology is intended to produce options and not limitations for the architect and the methodology used to evaluate the options (the vocabulary of structures now available) is still up to the architect as in a more conventional design approach.

3.3. Collaboration and process?

Collaboration between the engineer and architect is beneficial at an early stage in order to gather information to inform design decisions and to produce a more elegant design – elegant in the view that it effortlessly integrates a highly functioning structure with architectural intent. A Heavy
Design methodology is primarily intended to be carried out by an architect on their own to meet this end, but there are potentially many ways a collaboration could be carried out in the process. In the early phases of design, discussion with the engineer about the primary structural concerns of the site can be fruitful in determining the structural principles and/or materials with which to begin. A timber structure, for example, will not likely be a moment frame and if it has to span further, a composite type structure may be desired. If seismic behaviour is a serious concern then a starting point, which acknowledges this, is more likely to be successful architecturally. All these questions and more provide fodder for the design as it enters the planning (?) process. If engineers are incorporated as the process precedes more sophistication in the modeling and the design refinement may be possible – the fruitfulness of the collaboration depends to a large part on the interest and capability of those involved.

Since a part of the process is within the engineering software, this is particularly beneficial for communication of intent and for ease of the transition into the detailed engineering phase. The model of the project in the structural analysis program can be handed to the engineer for refinements and both parties can trade files seamlessly.

4. HEAVY CONCLUSIONS

The process described produces an attempt to incorporate gravity and materiality into architectural design by use of the technologies currently available to architects. Using algorithmic programming in architectural software, the variables related to the engineering behaviour of a system can now be incorporated into architectural form. This form can further be applied in differing conditions and configurations, being algorithmically adjusted live to vary the structure to respond to different conditions. A vocabulary of structurally-inspired architecture then results in a subsequent iteration through structural principles into architectural design. Bringing new architectural constraints to the method may generate further structures. Evolving algorithmic technologies in architectural software allows this incorporation and demonstrates a method of design which resonates with the New Structuralism - the idea of the designer, through the use of algorithmic design, mass customization and engineering analysis tools, moving closer to a material culture. ‘Heavy design’ uses a multiplicity of digital-age tools to produce a culture of making that allows easier translation from digital to real, thus bringing digital architects to the forefront of material understanding and application.
References

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