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VOXEL BEAM

Re-Fabricating a Structural Beam

A. HOSNY[1], N. JACOBSON[2] and Z. SEIBOLD[3]
[1,2,3] *Harvard University Graduate School of Design, Cambridge MA, USA*
{ahosny, njacobso, zsiebold} @gsd.harvard.edu

Abstract. Voxelbeam explores precedents in the optimization of architectural structures, namely the Sydney Opera house Arup beam. The authors research three areas crucial to conceiving an innovative contemporary reinterpretation of the beam: A shift in structural analysis techniques from analytical to numerical models such as topology optimization, the fundamental differences between digital and analog representations of structural forces, and the translation of structural analysis data into methods for digital fabrication. The research aims to re-contextualize the structural beam within contemporary digital platforms, explores the architectural implications of topology optimization, and proposes two fabrication strategies based on the analysis results – including automated off-site pre-casting and multi-material 3d printing.

Keywords. Digital Fabrication, Topology Optimization, Multi-material 3D Printing, Emergent Structural Design, Arup Beam.

1. Introduction

Contemporary designers work around amounts of data and computational power that far outweighs the utilization abilities of the construction industry. This disparity is particularly evident in structural engineering, which conversely limits a designer’s ability to utilize structure as an expressive design medium. If structure is to continue emerging from the hidden and concealed portions of buildings, designers would have the potential to incorporate more understanding and experiences of structure into design concepts.

The paper thus explores the type of digital craft and relevant fabrication strategies required to address such abundance of information. It examines a case study in optimization undertaken half a century ago to demonstrate a point of balance between the intellectual capacity for structural optimization and the physical capacity to realize a design. The research then tests the possibilities of our current technical capabilities for structural optimization design. The authors compare and contrast these capabilities with those of large scale construction methods and elucidate the chasm between the two.

2. Case study: The Arup beam

The Arup Beam is the outcome of an optimization exercise that took place prior to the integration of computation into the design processes. Constructed from reinforced post-tensioned concrete, and spanning nearly 150 ft, the beam was the result of a multidisciplinary design optimization exercise the included architects (John Utzon) and engineers (Ove Arup). Designed beginning in 1957 for the concourse of the Sydney Opera House, the Arup Beam was rationalized through an analytical structural analysis technique optimizing for compressive and tensile forces only. For a variety of aesthetic, performative and structural reasons, the beam features a varying section along its span. At the supports where bending moments are at their minimum, the beam section is U-shaped. This shape places a majority of material at the bottom of the beam, where compressive forces are at their greatest. At mid-span, where bending is at its maximum value, the section transitions into a T. The forces at the midpoint of the beam are flipped from the requirements at the beams end. Yuzo (2001) emphasizes the transition from U to T is achieved through a sinusoidal curve allowing for a smooth flow of forces along the span.

Figure 1. Formworks for concourse beams under preparation. "Viking ships upside down." Photo by Max Dupain [pending permission, (taken from Yuzo (2001) p.50].

Construction of Arup beam was cast in concrete on-site in commonly constructed plywood-sided molds (Figure 1). A post tensioned cable is strung opposing the compressive forces of the beam. Arup (1968) describes that the cable starts at the upper portion of the section of the U-shape and reach their bottom apex at the lowest point of the T at the center of the beam The method of constructing the mold closely represented the method for designing the beam. Plywood was 'lofted' between fixed geometry at stationary points that smoothly transitioned between the U-T shapes. This additive process created no waste of beam material and constituted a commonly use process of concrete pouring still central to modern construction. However the mold was highly customized and cast in whole. At 115ft long, Yuzo (2001) points out, this consumed a large area of the construction site for a system that would be used for this project only.

3. Research framework

The authors explored three areas crucial to conceiving a contemporary version of the Arup Beam (Figure 2). The first dealt with the shift from analytical structural analysis techniques used in the 1950's to contemporary numerical methods, such as Finite Element Analysis. This allowed the design domain to shift from the beam as a whole to a higher resolution of discretized elements comprising the beam. The second thread attempted to understand the fundamental difference between an analogue representation of structural forces, such as the Arup beams' sinusoidal curvature, and a digital binary system of 0's and 1's. This aims to re-contextualize the structural beam within contemporary digital platforms. The third was a two pronged approach concerned with the fabrication of results obtained from structural analysis. Our first aim in this regard was to construct a physical beam utilizing as much of the information garnered from our analysis techniques with common construction methods. A very complex and expensive formwork was utilized to realize the geometry of the Arup Beam. The authors speculated that a more generic and flexible formwork could conform to various optimized geometries whilst maintaining the practicality of construction. Our second aim was constructing a diagrammatic version of the beam whilst incorporating the maximum amount of structural data using additive manufacturing techniques, namely 3d printing.

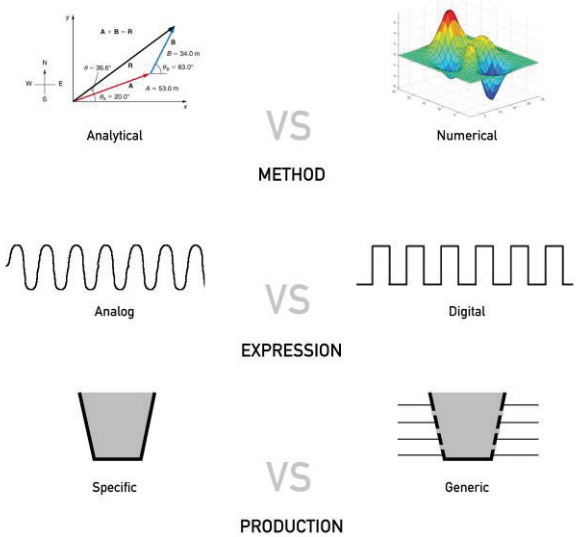

Figure 2. Theoretical framework.

4. Topology optimization

Through the process of optimization we find that there are underlying forms inherent in structures acting on physical geometric and material relationships. The famous and disputed demand that 'form follows function', mainly associated with architectural modernism in the 20th century seems to be most valid when looking at optimization methods. The Arup beam was optimized for compressive and tensile forces. Their method entailed explicitly placing concrete where it was most needed in compression and post tensioned cables where it was needed in tension. Today we have many options for optimizing a material structure either separately, as just a material or as a structure, or as one holistic system and down to the scale of individual microns. The conceptual process is thus rethought so as to implement optimization methods into the realm of architecture. The designer becomes an editor of constraints and the design emerges from the hierarchy of such selections.

Topology Optimization (TO) was chosen as a relatively young engineering optimization method with promising implementation opportunities in design due to its subtractive nature. Michalatos et al (2012) points out that using TO results as a concept generation engine also poses interesting fabrication challenges as many of these results are often discarded from a fabrication standpoint. Some recent projects have used TO results to generate architectural forms, most notably the concrete prototypes of Unikabeton and the 3D-printed steel building components designed by the engineering firm ARUP. In engineering terms, Topology Optimization is a structural numerical method describing the optimum material distribution in a given design domain with specific boundary conditions. It combines the widely used Finite Element Method (FEM) as an analysis module with an optimization algorithm. The design domain is discretized into finite 2D/3D elements. The optimization method aims to optimize the material density per element considering these as design variables in the given domain. Hence, minimum compliance of the structure as defined by Sutradhara et al (2010) is considered to maximize its stiffness while satisfying a volume constraint set by the designer. A full material density is represented by a value of 1 while a void element is assigned a value of 0. All values within this range can thus be interpreted as materials of variable densities.

The attractiveness of the TO method in conceptual design comes in at two levels. The first lies in its ability to synthesize structures without any preconceived shapes and hence the freedom to innovative high performance layouts as described by Liu et al (2014). In contrast to shape and size optimization practices, topology optimization operates on an empty canvas challenging the designer's initial instinct in conceiving designs. There is a certain appeal in discarding existing topologies that have accumulated through numerous designs over the years and the opportunity of a fresh start. It can thus be considered as a performance-based form finding function. The second level deals with the intriguing aesthetic language and expression that Bendsoe et al (1988) discusses which is that TO brings to the design discussion - in addition to other functional considerations such as optimizing material usage and cost.

5. Digital workflow

Digital tools developed for this study have been mainly concerned with creating interfaces between domain-segregated platforms that are otherwise not in direct communication. Within the design domain, Rhinoceros, a NURBS (Non-Uniform Rational B-Spline) modeling software and its parametric engine, Grasshopper, were utilized. Custom components were developed in Grasshopper using C#, a multi-paradigm object oriented programming language, to perform data exchange and parsing operations. Within the scientific domain, the TO routine used in this study was the "*An efficient 3D topology optimization code written in Matlab*" by Liu et al (2014) that utilizes the Solid Isotropic Material with Penalization (SIMP) method. This method was chosen as it is based on the heuristic relation between element density and Young’s modulus, providing a simple and clear basis for interpreting results. Within the routine, defining load cases is a cumbersome process requiring hard coding of each degree of freedom. Hence came the motivation to interface the code with a readily available CAD environment where such can be selected and assigned graphically.

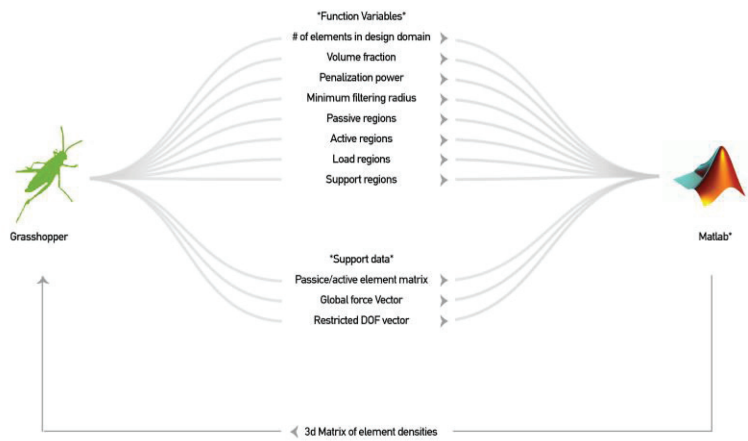

Figure 3. A diagram showing the architecture of the digital workflow. The problem variables are first defined in Rhino and is then sent to the topology script in MATLAB for optimization. The optimized element densities are then visualized back into the Rhino environment.

The user starts in the Grasshopper environment where multiple variables are defined (Figure 3). These include parameters for material structural properties as well as the desired resultant material quantity as a percentage of the entire domain. The authors calculated that the original Arup beam occupies roughly 27% of its dimensional extreme or bounding box. This ratio was used as a benchmark for running optimization calculations. Other TO parameters include the penalization power and filtering radius. While setting the penalization power at “3” ensures the resultant structure has well-defined edges, “1” allows for the true global optimum to emerge. Hence the values “3” and “1” were used to derive the result interpretation methods in 5.1 and 5.2 respectively. The complementary filtering radius parameter ensures the absence of artefacts such as checker-board patterns that usually result from penalization powers greater than “1”. Boundary and load conditions are also defined. Users draw any kind of closed BREP, such as a box, to demarcate supported/loaded nodes. Another supplementary selection allows the user to choose the number of degrees; X,Y,Z,XY,XZ,YZ or XYZ. As a structural beam problem, the authors simplified the load case to include boundary conditions at the edges with all degrees of freedom constrained, as well as a continuous distributed load on the beam's top face. These variables are then passed on to the TO code in Matlab. After the optimization algorithm has converged, results are sent back to grasshopper containing information on the density per element and the number of elements that comprise the "optimum" result. These densities can then be visualized within Rhino.

5. Result interpretation and digital fabrication

As criticism surrounding TO methods has always concentrated on the feasibility to fabricate its results, the authors explored two methods to interpret these results into tangible objects and iterate through them.

5.1. SINGLE DENSITY CONTOUR

The first method deals with choosing a specific density contour (or isovalue). Values below a specified density contour are set to be void while others above this value are set to be solid. It is a simplification of the more complex density variations the TO code outputs. These "0 and 1" structures can then be passed on to more traditional manufacturing technologies such as injection molding or CNC milling. A specific density contour can be chosen for the right combination of structural feasibility and architectonic qualities. Too small of a value will disintegrate a structure into discontinuous elements, too high a value will omit the hollow voids within. The computational representation of the finite elements that comprise the domain is based on voxels. Each voxel is calculated individually with control over the quantity of voxels and thus the resolution of information.

The first type of mold was a more traditional four part foam mold. A CNC router milled four open face segments of high density foam to create the negatives of the beam. Additional interior void segments were milled and situated within the larger mold. Then concrete was poured into the mold and allowed to set completely before de-molding and the interior voids were removed (Figure 4). It should be noted that this prototype exists as a structural diagram alone, as it would be difficult to fabricate using currently available reinforced concrete technologies. The research team suggests this as a solution for an as yet unknown advanced isotropic material.

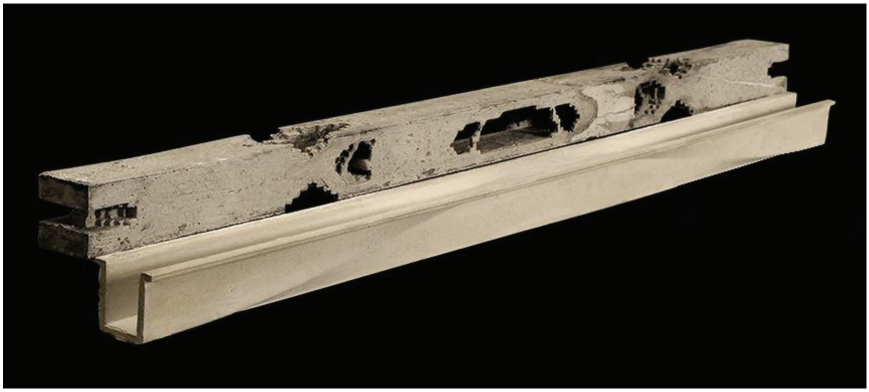

Figure 4. Voxel beam (top) and Arup beam (bottom) fabricated as negatives of a foam mold.

Following this experiment, the authors continued exploring a method for density contour fabrication with the added complexity of incorporating two materials into a single structural entity. While TO assume homogeneous isotropic material behavior, the possibilities of aggregating voxels by their tensile and compressive forces were explored. A CNC router milled two versions of a mold for one structure. The first mold contained the negative for one material, concrete, in compression and the second mold contained the negative for the first mold as well as the void for the second material, plaster, in tension. The materials, concrete and plaster, were used as proxies for actual materials that would be better suited to handle their respective forces. (Figure 5).

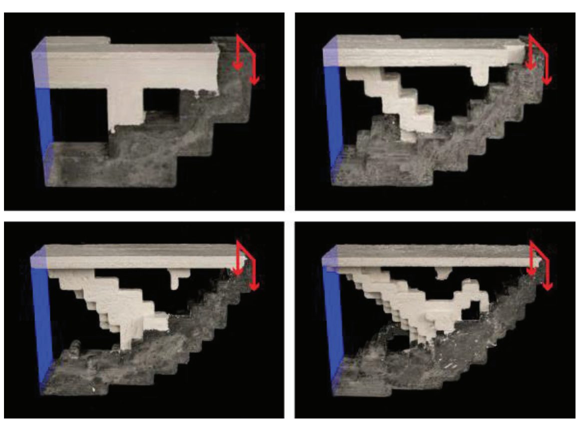

Figure 5. Cantilevered beams at various resolutions. White portions are in tension while those in black are in compression.

5.2. CONTINUOUS DENSITY FIELD

The second method the authors utilized for interpreting the results of TO is the continuous density field. This approach aggregates and combines densities to form groups with unique material properties. For example, elements with densities ranging from 0.0 to 0.3 are assigned a soft material while those between 0.8 and 1.0 are assigned a relatively harder material. This approach differs from the density contour method by not seeking to minimize the used material but redistribute material properties within the domain. Aesthetically the beams express a structural diagram of densities potential to address forces. This takes inspiration from hybrid materials such as steel-reinforced concrete, however through a TO method the individual materials come to the forefront in complex patterns.

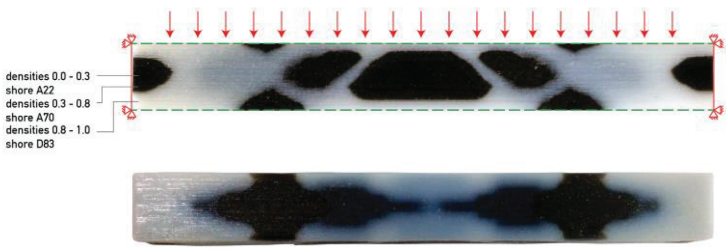

Figure 6. Optimized beam with 3 different material densities, hardest in white and softest in black. Side view (top) and bottom view (bottom).

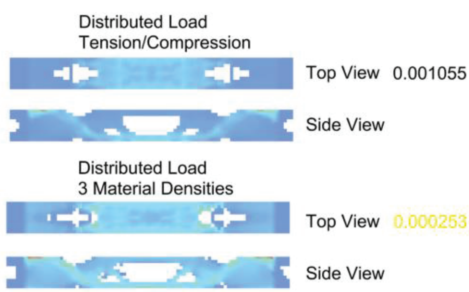

Figure 7. Analyzed tensile/compressive densities showing uniform stress distribution (top) Analyzed beam with 3 different densities showing a better deflection value (bottom).

An Objet Connex 500 multi-material 3d printer was used to fabricate the beams optimized under the continuous density field method (Figure 6). The resin depositing mechanism of the 3d printer allowed a high level of resolution in producing the prescribed density variations. The printer was hence able to capture, to a much greater extent, the optimization results without loss of details due to the threshold of densities. The limits to further refinements are now confined by processing power and additive manufacturing resolution. This method of optimization combined with the multi-material fabrication technique demonstrates a harmony between data-based design possibilities and fabrication ability.

6. Conclusion

Topology optimization in combination with multi-material 3D printing demonstrates the ability to realize a deeper understanding of structure in design, which advances the modernist demand of 'form follows function' by unlocking new structural functions and expressing these in new structural forms. Multi-material 3D printing demonstrates the greatest potential to realize designs with the highest level of information available to designers. However, this potential is limited in scale by the material mechanics and bed size of the printers. Attempts to realize such designs at a larger scale with alternative methods compromises the level of information and control of structure which directly affect their expressive and experiential possibilities.

The discourse on the values of new computational optimization and fabrication methodologies in structural design is futile if the ability to scale up such designs is not possible. If we are to realize the values of this research designers must gain a deeper understanding of engineering to more fully collaborate with engineers from the earliest point of design. Designers must also develop a deeper understanding of construction to assist in proposing new methods of fabrication that begin to close the gap between data/information and constructability.

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