the performance evaluation was carried out against a standardized design option. Thereafter, different shapes have also been compared to each other to further understand the responsiveness of daylighting for four different grid topologies. Results have shown that the rich correlation of the different simulation parameters employed in the optimization framework was also portrayed in the complex geometrical arrangements of the optimized solutions. Even though limitations and improvements have also been discussed to further enhance the form-finding capabilities of the implemented algorithm, the implemented routine still successfully discovered enhanced and novel configurations that offered alternative solutions to a reference design scenario.

REFERENCES

Caldas, L. G., and L. K. Norford. (2002). A Design Optimization Tool Based on a Genetic Algorithm. Automation in Construction 11 (2): 173–84. doi:10.1016/s0926-5805(00)00096-0.

Cuttle, C. (2002). Identifying the Human Values Associated with Windows. International Daylighting 5: 3–6.

Gagne, J. M. L., and M. Andersen. (2010). Multi-Objective Facade Optimization for Daylighting Design Using a Genetic Algorithm. Fourth National Conference of IPBSA-USA, New York City.

Galasiu, A. D., and J. A. Veitch. (2006). Occupant Preferences and Satisfaction with the Luminous Environment and Control Systems in Daylit Offices: A Literature Review. Energy and Buildings 38 (7): 728–42. doi:10.1016/j.enbuild.2006.03.001.

Goldberg, D. (1989). Genetic Algorithms in Search, Optimization, and Machine Learning. Addison-Wesley Professional. doi:citeulike-article-id:125978.

Hanna, S., and S. H. Mahdavi. (2006). Inductive Machine Learning in Microstructures. In Design Computing and Cognition '06, ed. J. S. Gero, 563–82. Springer Netherlands. doi:10.1007/978-1-4020-5131-9_29.

Kilian, A., and J. Ochsendorf. (2005). Particle-Spring Systems for Structural Form Finding. Bulletin of the International Association for Shell and Spatial Structures 46 (148): 77–84.

Kämpf, J. H., M. Wetter, and D. Robinson. (2010). A Comparison of Global Optimisation Algorithms with Standard Benchmark Functions and Real-World Applications Using EnergyPlus. Journal of Building Performance Simulation 3 (2): 103–20.

Villard, P.-F., W. Bourne, and F. Bello. (2008). Modelling Organ Deformation Using Mass-Springs and Tensional Integrity. Proceedings of the Fourth International Symposium on Biomedical Simulation. London,: Springer-Verlag. doi:10.1007/978-3-540-70521-5_26.

Rakha, T., and K. Nassar. (2011). Genetic Algorithms for Ceiling Form Optimization in Response to Daylight Levels. Renewable Energy 36 (9): 2348–56. doi:10.1016/j.renene.2011.02.006.

Rivard, H., C. Bédard, K. H. Ha, and P. Fazio. (1998). Shared Conceptual Model for the Building Envelope Design Process. Building and Environment 34 (2): 175–87. doi:10.1016/s0360-1323(98)00005-5.

Sargent, J., J. Niemasz, and C. F. Reinhart. (2011). Shaderade: Combining Rhinoceros and EnergyPlus for the Design of Static Exterior Shading Devices. In Building Simulation 2011, Sidney, Australia, 1–9.

US Department of Energy. (2010). Buildings Energy Data Book. Commercial Energy End-Use Expenditure Splits, by Fuel Type. http://buildingsdatabook.eren.doe.gov/docs/xls_pdf/3.3.5.pdf.

Webb, A. R. (2006). Considerations for Lighting in the Built Environment: Non-visual Effects of Light. Energy and Buildings 38 (7): 721–27. doi:10.1016/j.enbuild.2006.03.004.

Wong, S. L., K. K. W. Wan, and T. N. T. Lam. (2010). Artificial Neural Networks for Energy Analysis of Office Buildings with Daylighting. Applied Energy 87 (2): 551–57. doi:10.1016/j.apenergy.2009.06.028.

Yi, Y. K., and A. M. Malkawi. (2009). Optimizing Building Form for Energy Performance Based on Hierarchical Geometry Relation. Automation in Construction 18 (6): 825–33. doi:10.1016/j.autcon.2009.03.006.

WORK IN PROGRESS

AN INTEGRAL APPROACH TO STRUCTURAL OPTIMIZATION AND FABRICATION

Jelle Feringa
Delft University of Technology, Hyperbody / EZCT Architecture & Design Research

Asbjørn Søndergaard
Aarhus School of Architecture

ABSTRACT

Integral structural optimization and fabrication seeks the synthesis of two original approaches: that of topological optimization (TO) and robotic hotwire cutting (HWC) (McGee 2011; Feringa 2011). TO allows for the reduction of up to 70 percent of the volume of concrete to support a given structure (Dombernowsky and Sondergaard 2011). A strength of the method is that it allows one to come up with structural designs that lie beyond the grasp of traditional means of design. A design space is a discretized volume, delimiting where the optimization will take place. The number of cells used to discretize the design space thus sets the resolution of the TO. While the approach of the application of TO as a constitutive design tool centers on structural aspects in the design phase (Xie 2010), this process yields structures that cannot be realized within a conventional budget. As such, the ensuing design is optimal in a narrow sense; while optimal structurally, construction can prove to be prohibitively expensive. This paper reports ongoing research efforts on the development of a cost-effective methodology for the realization of TO concrete structures using HWC.

figure 1
The Unikabeton project.

figure 2
Surface structure derived from the milling process.

figure 3
Topology optimization of simply supported concrete beam.

figure 1

figure 2

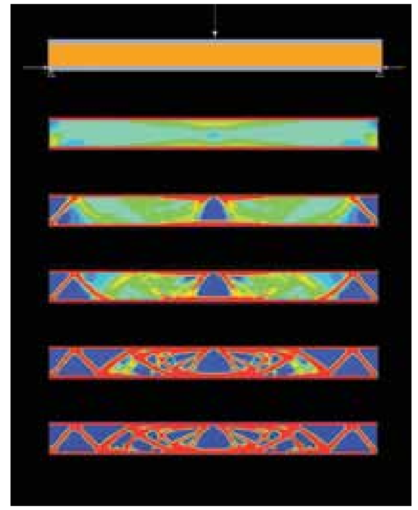

figure 3

1 INTRODUCTION

Earlier work on the Unikabeton project (Dombernowsky and Sondergaard 2011) suggests that the approach of milling the formwork offers questionable potential for large-scale employment. Even when deployed on immense facilities specialized in the production of ship hulls and thus of the scale required for architectural production, material removal would not scale beyond about three quarters of a cubic meter per hour.

This realization instigated a quest for finding a scalable, more economical approach to complex formwork. The notion of a coupled approach arose during the Fabricate 2011 conference, where the authors respectively presented work on TO and HWC. It became apparent that a coupled approach would be mutually advantageous, increasing the relevance for both TO and HWC simultaneously. The experience of building the protoSPACE project (Feringa 2011) showed that material removal of three to six cubic meters per hour is achievable, even with an improvised, rudimentary setup. The OptiCut project presented in this paper inquires into this potential. Earlier experience in the application of robotic milled formwork in the context of the Unikabeton project allows us to compare the two approaches. Our project suggests that hotwire-cut formwork is considerably more cost effective, given that the approach is essentially volumic.

2.1 Background

Gradient-based topology optimization is a computational method for structural form finding, currently utilized within (among others) the automotive, aeronautic, and naval industries for the design of lightweight vehicle structures and components.

From a design space—a discretized domain in which the design can take place—an optimal topology is produced by means of an iterative algorithm based on set performance criterias, material properties, and fabrication constraints. As such the approach holds relevance for the development of architectural structures. While several approaches for biologically inspired algorithms—such as ESO/BESO (bidirectional evolutionary structural optimization) (Xie 2010), the SKO method (soft kill option) (Baumgartner and Harzheim 1992), and the application of reaction-diffusion equations (Mitsui and Miyanaga 2011)—have been proposed in extension of the gradient-based topology optimization originally introduced by Bendsøe and Kikuchi (Bendsøe and Kikuchi 1988), comparative studies suggest that performance levels, result types, and effectiveness of the various approaches display little difference (Sigmund and Maute 2012). However, as gradient-based TO (due to its early historical

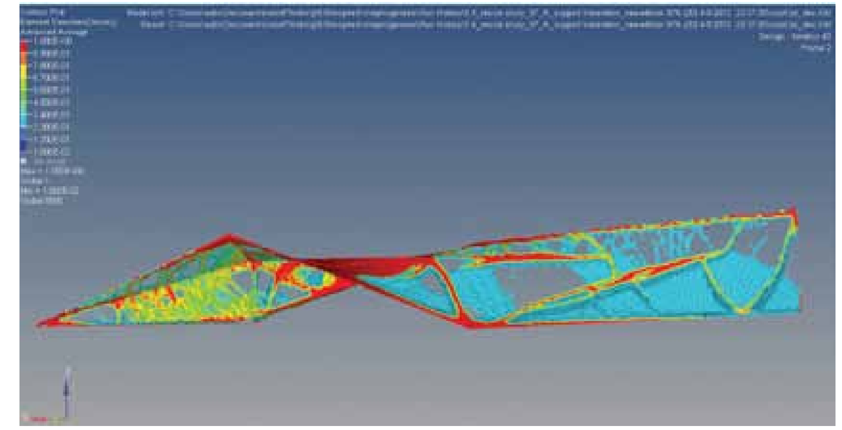

figure 4

figure 5

figure 4
Topology optimization result of the OptiCut prototype structure.

figure 5
Remeshed topology of the Opticut structure.

introduction) has been commercialized in existing CAE softwares, it offers significant reliability and workflow integration benefits over experimental methods, which has led to widespread adoption within the above-mentioned industries.

The gradient-based TO can be summarized as an iterative process, in which numerically simulated material is redistributed within a finite element model according to set optimization objectives, conventionally the minimization of deformation energy (Figure 3). The process assumes the definition of:

a) a design space, in which material is redistributed;
b) types and positions of supports;
c) set external or internal forces acting on the design space;
d) numerical properties of the concerned material;
e) optimization constraints (symmetry, fabrication constraints, penalty functions);
f) the optimization criteria.

Based on these conditions, material is incrementally organized on a finite element level, approaching a theoretical optimum, with which a maximum of structural stiffness is achieved with a minimum of material consumption. In preceding research under Unikabeton, the application of the method indicated potential reductions of material consumption of 60-70 percent of topology-optimized concrete structures, in comparison to conventional, massive equivalents, while respecting initial performance criterias (McGee 2011).

figure 6

Ongoing production of the OptiCut formwork.

figure 6

The process resolves in the materialization of high-density material zones (red in Figure 3) and low- or zero-density areas (blue in Figure 3), which are subtracted and mapped in a subsequent step, resulting in a new topology. For the development of the present project, topology optimization was performed using the Optistruct solver of the Hyperworks CAE environment.

3 PROTOTYPE DESIGN AND OPTIMIZATION

By virtue of these properties, the process of topological optimization substantively differs from established methods in civil and architectural engineering, such as size and shape optimization. A primary feature of this differentiation is the capacity of generating structural layouts that transcend classical typification, resulting in a conceptual shift from typological to topological thinking. This shift facilitates the generation of new spatial structures that accommodate configurations and boundary conditions, which lies outside the reach of empirical CAE design methods.

In an attempt to initiate a systematic investigation of the architectural implications for this recently opened field of structural design, the Opticut project targeted the identification of key configurations exhibiting the above-mentioned characteristics. A primary such case was found in the category of transitional configurations: geometries that describe the transition between typological identifiable elements.

As an exemplification of these investigations, the designspace of the Opticut prototype was constructed as a continuous geometry, derived from the transition between the geometrical primitives of point, line, and surface. This construct would form a hybrid constellation of three structural types—the wall, the canopy, and the semi-enclosed space—describing an incremental morphing between the typologies.

The design space was loaded with evenly distributed loads of dead- and windloads, assuming the material of a 35 Mpa steel fiber concrete. The optimized result (Figure 4) was remeshed and remodeled, describing the topology through configurations of doubly ruled surfaces.

4 ROBOTIC HOTWIRE CUTTING

The process requires a more extensive intermediary step of geometry rationalization. Constructing ruled surfaces from the double-curved mesh generated by the TO process adheres to specific constraints such as the Styrofoam block size, dimensions of the hotwire tool, and kinematic limitations of the robot. Interpreting the resulting meshes, however, is always an essential and unsurpassable step. Therefore it is only logical that aspects of realization such as the demolding of the formwork are taken into consideration. Ruled geometry is well suited to the task of casting concrete; in particular, demolding the formwork is guaranteed to loosen more easily. While we experienced considerable unforeseen additional effort in demolding the previous Unikabeton project, this aspect has been thoroughly integrated in OptiCut.

Not only does the double-curved geometry partially account for difficulties in demolding, the formwork itself was milled with a milling bit of a large radius, since otherwise machining times would end up prohibitively long even for a project of modest scale (12 × 6 × 3.5 m). A side effect of this is that the tracings left in the formwork frustrate the demolding process. The costly formwork and the additional effort of demolding offset potential material savings gained by the TO process. By developing a closely integrated approach of TO and HWC, we have been able to smooth out these obstructions considerably. As such, hotwire cutting is a powerful enabler. Given our relative inexperience with the process, we are optimistic that normative square-meter price for high-end concrete work is achievable, considering advances made in terms of robot code generation, while assuming geometry is suitable to the process—which implies that geometric sophistication potentially comes at little or modest additional expense.

4.1 Cost Aspects

While production remains ongoing at this writing, the projected machining time of the Opticut project is estimated at 70–75 hours of hotwire cutting time, whereas the Unikabeton project required 98 hours of milling time. As the milled surface of Unikabeton represents a total of 61.13m2 while the total area for the Opticut project represents 652m2, this equates to an approximate increase in production efficiency of ~600 percent. It should be noted that the Unikabeton molds were produced with a milling bit of a large radius, since smaller radii would result in a prohibitively expensive manufacturing cost. If a surface of equivalent smoothness to the HWC-produced cuts should be reached by milling, CNC machining hours would be multiplied by a factor of 2.5. While total cost may vary according to a number of parameters outside machining time, such as operator time, toolpath strategies, material cost, production overhead, etc., an extrapolation of cost directly associated with machining time thus indicates an 80–90 percent reduction using HWC over conventional milling.

5 GEOMETRY

Initially some skepticism had to be overcome regarding to what extent the meshes of the TO might be approximated by ruled surfaces. The process of geometry rationalization has gone through a number of increasingly canny interpretations of meshes resulting from the TO process, where the constraint of the rulings became progressively less of an issue. An example of such developing insight in rationalization is the interpretation of the bonelike columns typical for the TO process as hyperboloids, which are well suited for hotwire fabrication and match the original TO results satisfyingly.

A more challenging part of production preparation involved producing puzzle pieces, the dovetails that join the various EPS foam blocks. While generating the dovetails is easily automated, resolving the right assembly order of the blocks posed a greater challenge.

TO and HWC are remarkably coincident; in alliance, either method gains in relevance. Savings in reduction of the volume of concrete is to a considerably lesser extent offset by the prohibitive expense of the required complex formwork. A custom software for the interpretation of the ruled surfaces to robot code was developed especially for the OptiCut project. The software specifically optimizes the toolpath for reachability; the tool orientation has a degree of freedom over the axis of the wire, and it is important to take advantage of this freedom as it allows for considerable optimization of the reach of the robot.

The software nests the foam elements efficiently within the standard-sized foam blocks and performs a topological sorting of the ruled faces of the geometry. This clusters faces that logically can be cut in a single sweeping motion that does not require reorientation of the foam block. After the topology sort, the software tests whether an intermediary roughening step is required before grouping the faces. The roughening step is specific to robotic hotwire cutting, while with a traditional hotwire cutting machine no clashes between the tool and workpiece occur. The downside, however, is that to cut large blocks, a considerably larger machine is required, while a robot is a fairly compact machine, certainly in view of its reachability. Potentially a part-to-tool strategy, where the workpiece is held by the robot and moves toward one or several fixed hotwires, is an option worth exploring for the most challenging pieces. An additional benefit is that since the workpiece is held by the robot, the picking and placing of foam blocks and cut products can be largely automated.

Checks are performed for clash detection between tool and workpiece. Finally, the lead-in and lead-out are computed. The tolerances achieved are approximately a millimeter. This factors in a sighing effect when cutting the block, but more importantly, the robot is a machine that is both less stiff and precise than a gantry CNC machine. Compared to the earlier approach of milling with a large diameter for the Unikabeton project, HWC is more precise with the considerable advantage (mentioned earlier) of far smoother surfaces.

6 OUTLOOK

A continuation of the presented project under development is the concept of "not-so-lossy formwork." So far we have been dismissing the considerable capacity of the EPS material to withstand ample compression forces. The approach suggests a parallel to half-timber structures, where channels cut in the formwork are used for casting, while a large part of the formwork remains within the cast concrete structure. As such the usage of EPS and concrete is devised as composite.

A considerable limitation of the current generation of off-the-shelf TO software is that homogeneous materials are assumed. Recent developments in TO (Amir 2011) allow for heterogeneous materials, and research projects have been formulated to investigate the amalgamation of EPS, concrete, and reinforcement work. An approach under investigation is establishing a lossless production cycle, building on the development of parting agents developed by BASF and the Danish Institute of Technology promoting the usage of EPS that can be recycled without downcycling.

While creating prototypes for the presented project, we have started to investigate another take on hotwire cutting: hotblade cutting. Rather than using an end-effector mounted on a single robot, a blade is spanned across a pair of robots. When the distance between the TCPs of the robots is shorter than the length of the blade, an arc is formed, when either TCP shares a mirrored orientation. Both robots move synchronized with a rotary table; then double-curved surfaces can be approximated.

The merger of TO and HWC paves the way for an economical, material-efficient usage approach to realization of large-scale TO structures. Even though TO is a fairly well-established method within other disciplines (Bendsøe and Sigmund 2004), the integration of aspects of fabrication plays a critical role in driving forward the adoption of the approach.

Undeniably there is a trade-off involved with hotwire cutting; apart from the obvious limitations of ruled geometry, there are practical reservations to geometry where a large number of holes are involved. In such situations, either a lead-in or a lead-out is cut in the element that later on has to be mended, which comes at the cost of loss of precision and is more involved.

REFERENCES

Amir, O. (2011). Topology Optimization of Concrete Structures. In Euromech 522 Colloquium: Recent Trends in Optimisation for Computational Solid Mechanics. Erlangen, Germany: University of Erlangen Press.

Baumgartner, A., L. Harzheim, and C. Mattheck. (1992). SKO (Soft Kill Option): The Biological Way to Find an Optimum Structure Topology. International Journal of Fatigue 14 (6): 387–89.

Bendsøe, M. P., and O. Sigmund. (2004.) Topology Optimization: From Airplanes to Nanooptics. In Bridging from Technology to Society, eds. K. Stubkjær and T. Kortenbach, 40–51. Lyngby: Technical University of Denmark.

Bendsøe, M., and Kikuchi, N. (1988). Generating Optimal Topologies in Optimal Design Using a Homogenization Method. Computer Methods in Applied Mechanics and Engineering 71: 197–224.

Dombernowsky, P., and Søndergaard, A. (2011). Unikabeton Prototype. In Fabricate: Making Digital Architecture, eds. Ruairi Glynn and Bob Sheil. Cambridge, Ontario: Riverside Architectural Press.

Feringa, J. (2011) Investigations in Design and Fabrication at Hyperbody. In Fabricate: Making Digital Architecture, eds. Ruairi Glynn and Bob Sheil. Cambridge, Ontario: Riverside Architectural Press.

McGee, W. (2011). Matter and Making. In Fabricate: Making Digital Architecture, eds. Ruairi Glynn and Bob Sheil.. Cambridge, Ontario: Riverside Architectural Press.

Mitsui, K., and K. Miyanaga. (2011). Proceedings of the International Symposium on Algorithmic Design for Architecture and Urban Design (ALGODE), Tokyo, Japan, March 2011

Sigmund, O., and K. Maute. (2012, in review). Topology Optimization Approaches—A Comparative Review. In Structural and Multidisciplinary Optimization.

Xiaodong, H., and Xie, M. (2010). Evolutionary Topology Optimization of Continuum Structures: Methods and Applications, 174–87. Wiley-Blackwell, John Wiley & Sons, Inc.