

Design and Fabrication of Topologically Optimized Structures; An Integral Approach

A close coupling form generation and fabrication

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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). TO allows for the reduction of up to 70% of the volume of concrete to support a given structure (Sondergaard & Dombernowsky 2011). A strength of the method is that it allows 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), the outcome of this process are structures that cannot be realized within a conventional budget. As such the ensuing design is optimal in a narrow sense; whilst optimal structurally though, construction can be prove to be prohibitively expensive.*

Keywords. *Topology optimization; robotics; hotwire cutting; EPS formwork; concrete structures.*

INTRODUCTION

Earlier work on the Unikabeton project (Sondergaard and Dombernowsky 2011) suggests that the approach of milling the formwork offers little 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 was brought about with the event of the Fabricate 2011 conference, where the authors respectively presented work on TO and HWC. It became manifest 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) learned that a material removal of 3 to 6 cubic meters per hour is achievable, even with an improvised, rudimentary set-up. The OptiCut project presented in this article inquires 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 an essentially volumic.

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 that 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 demoulding of the formwork are taken into consideration. Ruled geometry is well suited to the task of casting concrete in particular demoulding the formwork is guaranteed to loosen more easily. While we experienced considerable unforeseen additional effort in demoulding the previous Unikabeton project, this aspect has been thoroughly integrated in OptiCut.

Not only does the double curved geometry partially accounts for difficulties in demoulding, 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) project. A side-effect of this is that 3 Cost aspects 4 the tracings left in the formwork frustrates the demoulding process. The costly formwork, the additional effort of demoulding offsets 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



Figure 1
The Unikabeton Project.



Figure 2
Structure from the milling process.



Figure 3
Ongoing production of the OptiCut formwork.

Figure 4
Topological optimization result of the OptiCut prototype.

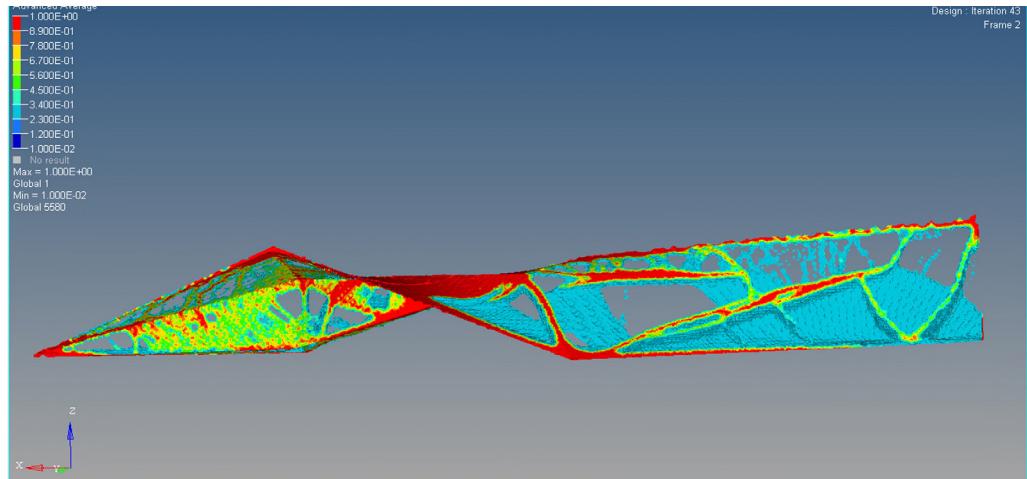


Figure 5
Post rationalized optimization results.



we're 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.

COST ASPECTS

In comparison to the Unikabeton project we've been able to realize a reduction in formwork cost of 80%, where the decrease in expense roughly equates the shortened production span. The OptiCut project presents a six fold increase in terms of volume in comparison to the Unikabeton project,

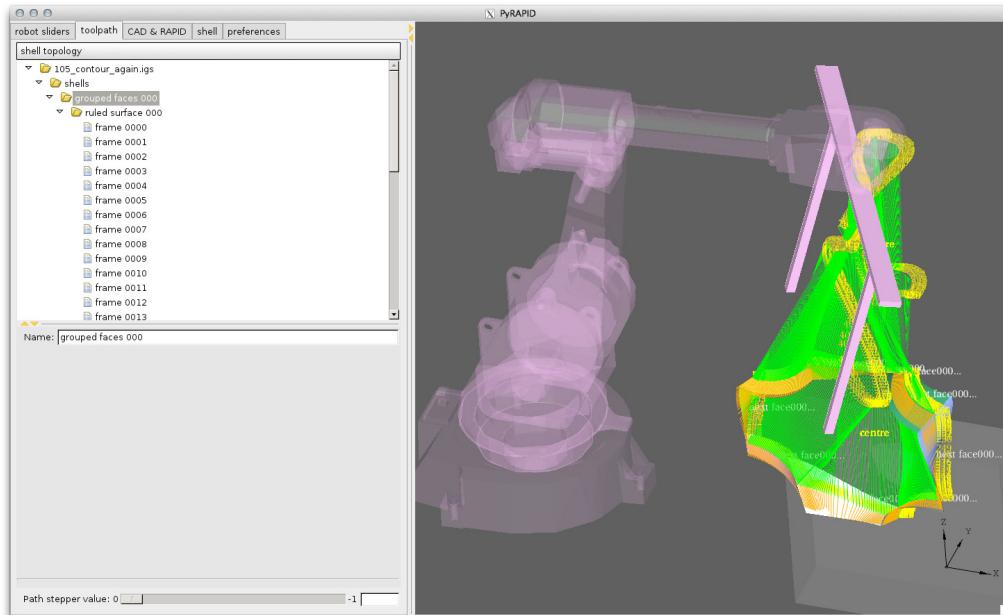


Figure 6
PyRAPID software facilitates the generation of robot code from introspecting the CAD model.

while the production of the formwork was of comparative cost.

GEOMETRY

Initially some skepticism had to be overcome 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 bone like columns typical for the TO process as hyperboloids, which are well suited for hotwire fabrication and matching 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 remarkable coincident; in alliance either method gains in relevance. Savings in reduction of the volume of concrete is to a considerable 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, it's 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 do not require re-orientation 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 towards 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 is computed. The tolerances achieved are approximately a millimeter. This factor in a signing 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 earlier mentioned considerable advantage of far smoother surfaces.

OUTLOOK

As a continuation of the presented project under development is the concept of “not-so-lossy-formwork”. So far we’ve been dismissing the considerable capacity of the EPS material that can 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) allows for heterogeneous materials and research projects have been formulated to in-

vestigate the amalgamation of EPS, concrete and reinforcement work. An approach under investigation is establishing a loss-less 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 down-cycling.

While creating prototypes for the presented project, we’ve 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 TCP’s 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, than 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 limitation of ruled geometry there are practical reservations to geometry where a large number of holes are involved. In such situations either a lead-in / 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.

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