Kevin Noack
Research Assistant and PhD student
Geometric Modeling and Visualization
Technische Universität Dresden
Institute of Geometry
Germany

Martin Friedrich Eichenauer
Research Assistant and PhD student
Geometric Modeling and Visualization
Technische Universität Dresden
Institute of Geometry
Germany

Daniel Lordick
Prof. Dr.-Ing.
Geometric Modeling and Visualization
Technische Universität Dresden
Institute of Geometry
Germany

Optimization of Voids in Concrete Ceilings – a Geometrical Approach

The task to reduce the material consumption in the building industry is urgent. Conserving concrete saves nature and money. To reduce the consumption of concrete in buildings we design hollow bodies in ceiling structures. In a free geometrical optimization process we restrict to those forms which can be fabricated in half shells. Our main goal is the best concrete saving ratio with respect to the restrictions of the building process. We show some possible forms and focus later on the better possibilities, the crossing channels. A smoothing step to avoid edges that cause stress peaks will raise the concrete saving even higher. We evaluate the use in technical applications under some questions like the concrete ventilation or the problem-free traversing in the fabrication process.

Keywords: *voided biaxial slab, hollow ceiling, form optimization, concrete structures, smooth structures, half shell fabrication, finite elements analysis, Cross Channel technology, concreting.*

1. INTRODUCTION

Common concrete buildings are fabricated of blocks of solid concrete. This is an inefficient, expensive and non-sustainable way of fabrication. Especially, the energy consuming material cement causes problems. The task to reduce the consumption of concrete in buildings without losing stability is a crucial factor for a smaller carbon footprint of the building industry in general.

To reduce the dead load of buildings there exist some ways. You can use other kinds of concrete with changed ingredients or a lighter reinforcement. By using negatively curved shapes, created e.g. with non-developable ruled surfaces, shells can be built light, load bearing and efficient. In many technical questions, the wanted concrete is fixed and should not be altered. An illustrating example for this problem are concrete ceilings in an arbitrary building, for example an office block.

It is beneficial to reduce the weight of ceiling stabs to implement voids. This fact is well known for a long time and used for example in brick ceilings or prestressed concrete structures. The fabrication of steel-reinforced concrete requires a high energy and resources effort, especially in the cement and steel production. Building with ferroconcrete brings high bearing loads but also high dead weight. By using voids with the Cross Channel pattern, you can reduce this dead weight which is responsible for a large part of the bearing loads.

The creation of CC ceilings with voids in perpen–dicular disposals enables a new, very light support stru–cture, which consists of two local connected layers. This structure is based upon the stress and loads on the ceiling (form follows force). You can find some models using this technology in the living nature, too (biomimetics).

The advantages of the weight reduction of ceiling slabs by using voids are well known for a long time. The hollows were realized by brick stones in steel-stone ceilings. By using the technology of prestressed concrete higher spreads with monaxial tensioned slabs are possible. A void system with biaxial tensioned ceilings exist since nearly 10 years. In this technology of Cobiax® the voids are balls shaped.

A solution for this issue are voids in the ceiling. In [19], the author describes how to do it: They should replace the concrete to save material. Our approach is eco-friendly and sustainable. For that reason, we use recycled scrap paper for the voids. This should be made of that material and filled with scrap paper's fibres, too. If placed in a proper manner then there is no problem in heat or noise protection.

Material should be saves on the points where it is not needed. This means on places where the local bearing load and the stress are low. There are tractions on the upper side and compression forces on the lower side of the ceiling, so we place the void structures between two layers of concrete. This allows us to save material in the middle layer but fulfils the load-bearing condition of the ceiling. In addition, the voids should be placed between two layers of solid concrete to avoid visible holes in the structure. With the voids we shrink the deadweight of the whole structure and this leads to lower internal stress. The result is the same load carrying capacity with reduced dead load.

We assume that our whole ceiling is a cuboid. Starting from zero we want to find a form that combines a high saving of concrete (or comparable material), the same load bearing capacity like a solid concrete ceiling and the possibility to use it in technical applications. The last point means that the concreting step must be possible without problems in the concrete traversing or the one-step-production. There are several approaches to gain this with lightweight structures, especially with hollow ceilings. While Bubbledeck®, Cobiax® or

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Correspondence to: Kevin Noack, Research Assistant, Geometric Modeling and Visualization, Technische Universität Dresden, Institute of Geometry
E-mail: kevin.noack@tu-dresden.de
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Beeplate® focus on separated voids, this contribution deals with a solution where the void is generated by a system of intersecting tubes, called Cross Channel (CC) technology. This idea originates from hollow ceilings, which are based on extruded forms. We follow the headline 'form follows force' of the project SPP 1542.

We are free in finding the perfect shape and place for these voids. We will locate them in the middle of the ceiling. This means there is concrete near the edges, where the most stresses and loads are located. We now allow a free-form optimization with the restrictions to produce half shells, which means we need symmetric patches. The restriction is another sustainable point. Half shells can be transported more efficient and for that, they save money and spare the environment.

In the next chapter, we start with an interesting example of already existing hollow ceilings. The idea works quite well and fulfills technical conditions in building processes. The geometry is not optimal, though. We show a way to improve it. After that, we start from zero in creating a hollow ceiling. The free geometrical optimization leads from simple ideas to interconnected voids and globally smooth structures that are related to the starting geometry. With that combi–nation of theoretical thoughts in mathematics with tech–nical applications from the civil engineering, we give a considerable contribution in the wide interdisciplinary field of building technology.

2. MOTIVATION: CROSS CHANNEL STRUCTURES

The motivation of our geometrical optimization are hollow ceilings. In an already existing way they can be fabricated with Cross Channel (CC) structures as voids. The CC structures are part of the SPP 1542 to which this paper belongs. These hollow bodies are made and filled with recycled scrap paper as sustainable approach. The structure was originally designed by engineers in reference to technical problems without the thought of mathematical optimization. More detailed information about the project and hollow ceilings with CC structures can be found in [18].

We present the technique with the previous geo–metry. An overview about the Finite Elements Analysis of forces and displacements is included. We show how the voids are fabricated and concreted. A smoothing step to optimize the structure closes the chapter and opens the door to the free geometrical optimization in the next section.

2.1 Technical Meaning

We start with interconnected void structures that use crossing channels in technical applications. The so-called Cross Channel (CC) technology allows us to save a great volume of concrete by constant payload overall the ceiling. CC structures are the best compromise between the placing of hollow bodies made of sustainable scrap paper and the possibility to concrete the ceiling without problems like a proper concrete traversing or ventilation.

The CC technology describes the geometric feature of these plated structures. There are crossing pipe channels inside which lead to a material-saving building style in comparison to plates with the same thickness made of massive concrete. To produce CC structures you have to compose two half shells with a technique like an overlapping joint, gluing together or some plug connections. This way of production has the advantage that the half shells can be transported very efficiently. Transferring that technology on concrete supporting structures contains a huge potential.

This chapter starts with the geometry of crossing cha–nnels which has been researched. We define their dimen–sions, calculate some exemplary concrete saving and show the concreting process of the initial structure. A simula–tion with different load cases is included. We illustrate the fabricating and concreting steps of the initial geometry. In the last step, we smooth the structure and calculate the improvement with respect to the optimization task.

2.2 Initial Structure within the SPP 1542

The starting point is the CC structure, which was exa–mined within the SPP 1542 by Juergen Ries and Wolfram Jaeger. This example will serve as the refe–rence structure for further optimization steps.

The whole ceiling is a cuboid. The CC structure should be used in a way that there is an area solid concrete in each direction from it. Therefore, you could look at it as the hollow body (the crossing channels) that lies in the middle of the ceiling.

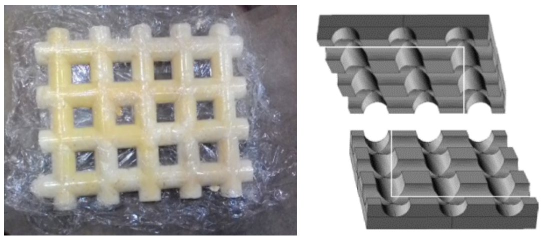

Figure 1. Left: CC structures, made of polyurethane foam. Right: The two forms to fabricate the structure. Cited from [19].

The channels are cylinders with the basis as a circle which is defined by the radius $R_1 \in R_+$. It follows the height of the structure is $h = 2 \cdot R_1$as the diameter of the circle. The holes in the structures are quadratic in the top view. Their side length is denoted by $d_2 = 2 \cdot R_2 \in R_+$ as the shortest distance between to tubes in the same direction. The structure is symmetric by cut–ting through the layer on the half height. It is also symmetrical in vertical orientation to axis who cut through the middle of the cylinders in a plumb way. The distance between theses axis (in horizontal direction) is given by $d_r = 2 \cdot r$ with the property $r = R_1 + R_2$. The cylinders in the length's direction have the same parameters R_1, R_2 as their companions in the width's direction.

For the calculation of the concrete saving, we need to define a reference block. This is a box with the void plus one layer of massive concrete above and one below the hollow body. It consists of n_1 channels in x- and n2 channels in y-direction. We renounce to use a fringe of solid concrete along the body but will give some conc–lusions to that case later. So the relative saving can be computed via:

$$Q_1 = \frac{V_{P_1}}{V_C} \in [0,1] \tag{1}$$

We assume, the heights of the upper and lower layer h_0 of solid concrete are similar and external given. They should be at least 50 millimeters to guarantee the possi– bility of their concreting. In addition, we fix h to be an even multiple of 10 millimeter. The volume of scrap paper follows the rule

$$V_{P_1} = \pi \cdot R_1^2 \cdot \left(n_x \cdot L_x + n_y \cdot L_y - 2R_1 \cdot n_x \cdot n_y\right) \tag{2}$$

The following table shows some values for Q_1 depending on the choice of R_1 and h_0 by given $r = 55$, $n_x = 3$, $n_y = 4$. Then we calculate $L_x = 330$, $L_y = 440$. The entity of length values is millimeter. Some exem– plary calculations can be found later in table 1. A quasi-static simulation can be found in [18], where the author treats with the material model under different load case scenarios.

2.3 Fabrication of CC structures

In the the prefab factory in Flöha we connected two half shells respectively with laces to ensure their tightness for the concreting. This was done by hand for each void on its own. Figure 2 shows the steps.

Figure 2. From right to left you can see the steps from the half shell to the interconnected void. We did a lot of handwork to seal them with laces. Photo by Jürgen Ries.

The half shell's connection with laces was just a makeshift. In the next step in the project the half shells should be stacked together with an overlapping joint. This is done concrete dense without any relocatabiliy in the horizontal direction. It can be manufactured easily and fastly. The concrete ventilation is warranted.

After the trial concreting of some exemplary CC structures as void bodies, we give some insights on the realized geometry. They can be found in figure 3. The scrap paper kept tightly closed against humidity, the concrete could traverse without any circumstances.

The completely concreted ceilfaing with CC structures is reinforced with steel fibres. The work was done properly, the compression with the riddling table and the concrete vibrator went well.

A testing with area load and block loads with four load points will be done. After the analysis of the resulting stress-strain-curve, the maximal load bearing capacity will be tested until the ceiling's failure. We include an evaluation of the thickness, the number and the location of the appearing cracks. This leads to an experimental verification or correction of the best spots to place the CC structures.

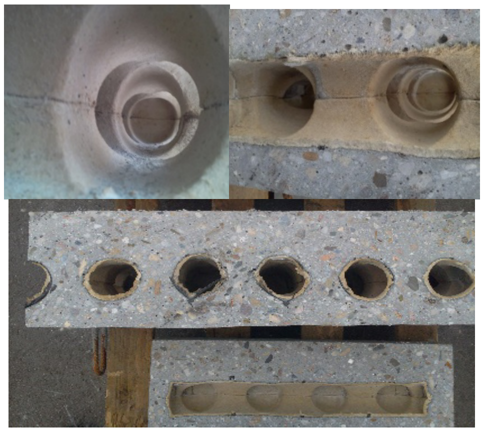

Figure 3. There are some insights in the concreted struc– tures. The three layers of solid concrete in the upper and lower layer together with the CC structures of scrap paper can be seen. Photos by Jürgen Ries.

2.4 From square to circular holes

The initial geometry can save nearly a quarter of concrete in the reference block. This is a great result but there is some space for improvement left. An issue is the fact that you have four edges in each hole (in the top view) which are not smooth. In these edges, you have a higher stress level but you want the stress to be uniformly spread along the structure. To avoid this you can create another CC structure by rotating semicircles with radius R_1 along an axis with a shortest distance R_2 and the distance $r = R_1 + R_2$ from the circle's center to that axis (see figure 4). The height is $h = 2 \cdot R_1$.

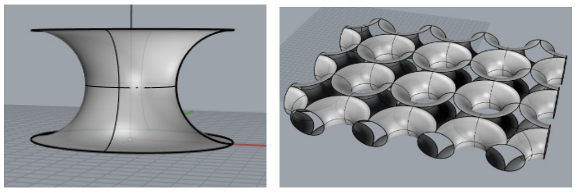

Figure 4. Left: One hole as rotating semicircle. Right: Smoothed CC structure.

The difference to the previous form lies in the way to model the structure. Now the void's hole is created. By putting some rotation bodies together, you receive cylinders in x- and y-direction, the crossing channels. Their notation can now be transferred to the new ver– sion.

The plane spots on the upper and lower side of the structure (see figure 4, right) can lead to some problems in a proper concrete's ventilation. They are too large to guarantee without simulation that all air bubbles will disappear through the densifications process. We plan to test it in a prospective experiment.

We reduce the area of the holes for the concrete by shrinking the square (in the middle of the opening) to the incircle. It is obvious that now the whole opening has a smaller volume than the initial version. We want to compute the spare of concrete with the formula

$$Q_2 = \frac{V_{P_2}}{V_C} \in [0,1] \tag{3}$$

The gross volume is still calculated via (2) but you need a new equation for the scrap paper's volume: The volume of the hole as a rotation body can be received from

$$V_{Hole} = 2\pi \cdot R_1 \cdot \left(\frac{2}{3} R_1^2 - \frac{\pi}{2} r R_1 + r^2 \right) \quad (4)$$

In each void you have $n_x \cdot n_y$ full holes. The overall volume of all holes needs to subtracted from the box of the void with size $L_x \times L_y \times h$. The result is

$$V_{P_2} = L_x \cdot L_y \cdot 2R_1 - n_x \cdot n_y \cdot V_{Hole} \quad (5)$$

In table 1 you can find some exemplary calculations of Q_2 to see $Q_1 < Q_2$. The value

$$Q_E = \frac{Q_2}{Q_1} - 1 \quad (6)$$

stands for the concrete you save more by smoothing the holes (in comparison to Q_1).

Table 1. List of some values for the concrete saving with r=55, n_x=3, n_y=4 and their extra saving.

R_1	h_0	h_p	Q_1	Q_2	Q_E
25	55	169	0.182	0.201	0.147
30	50	160	0.248	0.274	0.111
30	60	180	0.220	0.244	0.111
35	55	180	0.281	0.306	0.089

In the unsmoothed case, we could spare 24.8% of concrete. The smoothing step gives us an extra boost to 27.4%. This means we could raise the effect by another 11.1%.

We see that a higher value for R_1 implies for fixed r a smaller hole for the concrete to flood through and a higher saving Q_1. If you only vary h_p it can be seen that a higher value for h_0 leads to a smaller saving Q_1. This effect is obvious because you only raise the volume of concrete. The same procedure gets to similar results by putting a fringe along the void. If you raise ceteris paribus r then you shrink Q_1.

Due to the fact that $\frac{\partial Q_2}{\partial R_1} > 0$, $\frac{\partial Q_2}{\partial h_0} > 0$ and $\frac{\partial Q_2}{\partial r} < 0$ holds, the same rules like in chapter 2.1 are valid. The extra saving only depends on R_1 with the rule $\frac{\partial Q_E}{\partial R_1} < 0$.

2.5 Example: CC structures in the whole ceiling

For a complete support structure, you need to put some hollow bodies along to each other. Then you need a surrounding of solid concrete in each direction. The ceiling we look at has three blocks of size 1300 × 3900 mm × 160 mm which are merged to a support structure of size 3900 × 3900 mm × 160 mm with R_1 = 30 mm, r = 55 m and h_0 = 50 mm. In figure 5, we image the top view of such a ceiling.

In a next step the whole ceiling should be tested with suitable simulation software. Because of the high computation effort we will use a quarter model. A conc–reting and experimental testing like it was done with the unsmoothed CC structures is planned.

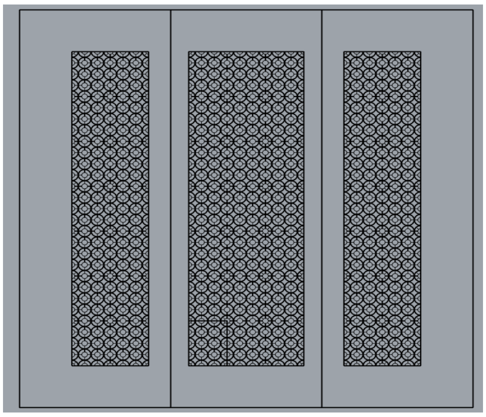

Figure 5. We see the support structure with three blocks in the top view. In the left and right parts are 2×7 and in the middle part 3×7 voids obstructed. One hollow part in the lower left corner of the middle part is tagged.

3. GEOMETRICAL OPTIMIZATION

For a good structure, on the one hand, we need shapes that allow to save as much concrete as possible. On the other hand, it needs holes for the concrete's top-down traversing. So a ball cannot be used.

After the definition of the problem, we focus on suitable forms. After some simple examples, we con–centrate on interconnected voids because they get better results with respect to the optimization task. The already existing Cross Channel structure will be the result.

3.1 Optimization problem

Our main task is the decrease of the total deadweight of the ceiling. This means we want to shrink the volume V_{con} (or the mass analogue) of the needed concrete as much as possible with respect to the problem's restric–tions. Because our void structures are made of light scrap paper, we ignore its mass. They are lighter than concrete, so more paper implicated less concrete and less dead load.

We define the problem via the equation

$$V_{Con} \rightarrow \min \quad (7)$$

with the restrictions that the total load bearing capacity of the whole ceiling C_{total} should at least remain on the unvoided level

$$C_{total,voided} \geq C_{total,solid} \quad (8)$$

and the existence of a symmetry axis in horizontal direction to enable a half shell fabrication. Short: We want the highest concrete saving with minimal stress.

We rewrite the problem (7): Our focus is not the con–crete's volume. We want to compute the relative saving of concrete. For that, we compare the volume of the solid concrete ceiling with the voided one. So the relative saving as quotient Q can be computed (like (1)) via

$$Q = \frac{V_P}{V_C} \in [0,1] \quad (9)$$

as the relation of the volume of scrap paper V_p (as the value for the absolute saving of concrete) to the block made completely of solid concrete V_c. The value for Q needs to be calculated on a reference block. It will be defined later but depends on the void's geometry.

We want to calculate the net volume $V_N=V_C-V_P$ of the concrete in the block now. The gross volume can be computed via the formula

$$V_C = L_x \cdot L_y \cdot h_p \tag{10}$$

with the length $L_x = 2r \cdot n_x$, width $L_y = 2r \cdot n_y$ and plate height $h_p = 2R_1 + 2h_0$. The formula for h_p implicates that the voids should not be visible on the fabricated ceiling. So, we should place at least a small layer of solid concrete on its upper and lower side.

3.2 Interconnected Tori

We start with a ceiling of solid concrete. Its form is a cuboid with scales $L_x \cdot L_y \cdot h_p$ like used in common ceilings. The optimization task will be to place one or some voids in the ceiling to reduce its dead load.

The form we choose is free but has to be fabricated as half shells. We need to ensure a proper top-down concrete traversing. The concreting will be done in one step. This means that the voids (and the reinforcement, too) are fixed at the time the concrete is filled in the form. On the upper and lower side of the void structure there shouldn't be larger flat areas because they obstruct the concrete ventilation.

The void's position. In the first step, we place one void in the cuboid ceiling. It is easy to see that this can't be the optimal way because the amount of saved concrete is either not high enough or the structure is too big that the ceiling becomes instable and cannot carry the same loads as the original solid concrete structure.

Figure 6 shows two naive starting ideas. We can place a torus that acts like a pillow in the middle of the block-like ceiling. We can change its dimensions or displace it to a non-centred position. On the right side, you can just cut a cuboid out of the whole ceiling. This is easy to fabricate but implicates many problems in the technical realization.

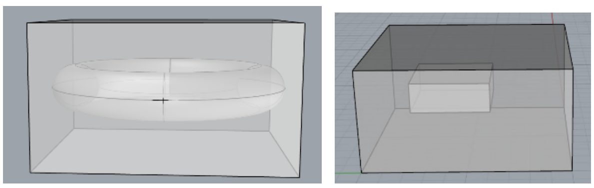

Figure 6. Some void structures with symmetrical patches. Left: A torus, symmetric in each direction. Right: A cuboid as hollow structure, located not centered.

We concentrate on cuboid ceilings with loads on the borders where walls meet the ceiling. No pillar will support the ceiling in some inner area. Due to this fact it is obvious we place the voids symmetrical to the ceiling's centre. The cuboid in the right figure 7 needs to be centred to fulfil that requirement. In the normal case, all stresses are symmetrical to the centre.

Our ceiling will be simulated as an in-situ concrete slab. It is all-round partial fixed. In figure 7 (left), we show the quarter of the ceiling with its boundary conditions. In the right side of figure 7 we show that the deformation spots are near the borders. It means on these places we need to be very careful if we want to reduce the concrete there. We used the finite elements analysis-software ANSYS.

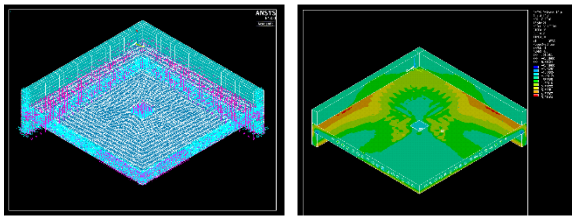

Figure 7. The quarter ceiling is implemented in ANSYS. The dimensions are 4.5 m × 4.5 m. In the center position there is a discharge spot of 0.2 m × 0.2 m. Left: The boundary conditions can be seen. Right: The payload and block deformation are simulated for the slab's top. ANYSY simulation by Juergen Ries (SPP 1542).

The voids should be sited where the payload is relatively low. A good spot is the middle of the ceiling. Near the fringe with neighbouring walls, the payload is high and the stresses have a high impact. The motto is: Take away the concrete where it is dispensable. The lower dead load leads to lower stresses and payloads. This effect gives us the same bearing load capacity with reduced deadweight.

Interconnected voids with a tori geometry. To raise the volume of saved concrete by preserving the load bearing capacity we want to place more than just one void in the structure. This also follows the engineering approach to function-oriented. The new form should contain a certain amount of voids. All of them have the same geometry because elsewhere there is an obvious problem with the optimization task.

In the nature the rocks in the river are polished round. This is a sign that smooth things fulfils our task better than edgy ones. We focus on smooth and round objects. This can be tori or rotation bodies of semicir–cles. We are not using hyperbolic geometries because they lead to many practical problems in the concreting or fabricating process. For example, a hyperboloid of one sheet has some disadvantageous stress peaks that might need some support structures.

It is not beneficial if the voids are treated as single ob–jects. In figure 8, we image four tori that aren't connected to each other. This means a high effort in placing them in the structure before the concreting starts. Therefore, a better way would be to intersect the void structures.

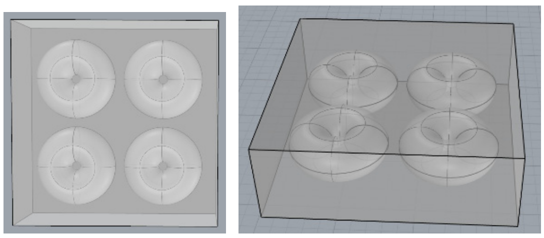

Figure 8. The torus of figure 6 (left) is now replaced by four smaller tori. They lie centered

The difference between the figures 8 and 9 are the overlaps. We skip the intermediate step of bothering voids and go directly to intersected ones. The displacement gives us more space to place even more voids. So we can raise the concrete's saving by using interconnected voids.

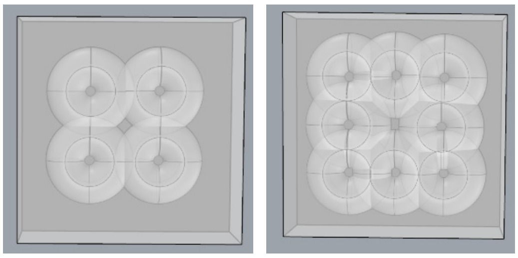

Figure 9. The tori of figure 8 are shifted in a way that they intersect. Left: Only the four tori are displaced. Right: By inserting four more tori, we create a more efficient void structure.

We want to remember to the face that our void needs a hole for the concrete to traverse top-down. This hole has to be at least the diameter of the largest aggregate in the concrete. On the building site this value is multi–plicated by a factor to ensure the concrete's traversing.

We want to point out that the CC structures are now modeled by tori as the real scrap paper part. This is an important disparity to the structure in figure 4 that is defined by the holes as rotating semicircle.

A possible reader's question could be why we are using round objects like tori. They are just circles rota–ting around a central axis. We focus on these objects because a round or smooth geometry gives us some ad–vantages: we avoid edges, which cause problems in a proper concrete's traversing, and we can spread the stress more uniformly. We avoid local peaks where some other support structure would be needed. Because of this fact, we also want the holes in the voids to be smooth. The central spot in figure 9 (right) needs an adjustment because the central hole is rectangular. It can be seen in figure 10. We place another tori in the middle.

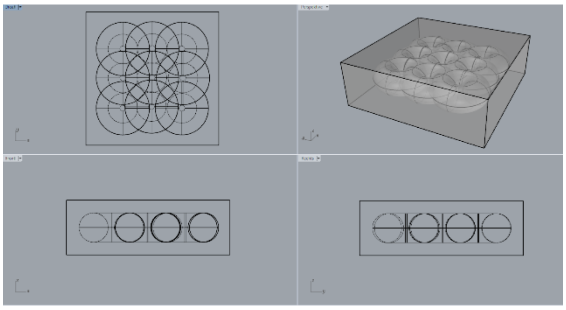

Figure 10. Inserting the ninth tori in the middle leads to a structure of crossing channels if the torus' defining circle's radius is large enough. We show all views that Rhinoceros3D offers us.

We detach from the top view. By viewing on the structure from the front or the side, the combined tori look like cylinders in x- and y-direction (with exception to the outer ones in the respective direction). This leads to the smoothed CC structures of the previous chapter. They play the dominant role in this paper because of the advantages they give us as interconnected voids. We can fabricate them as half shells out of scrap paper.

3.3 Smoothing and rearranging the structure

We found a promising form by combining the tori. This brings us the CC structures. We remarked in section 2.4 that the structure in figure 4 (right) has some plane spots on the upper and lower side.

To avoid this, we implemented another method. We smooth these areas with Bézier curves in vertical direc–tion. After the intersection into an uniform amount of points of each curves we smooth horizontal with NURBS (Non-Uniform Rational B-Splines). Figure 11 shows the new geometry. We want to point out that the interpolation was done with splines that are tangential to the z-axis at the centre lines.

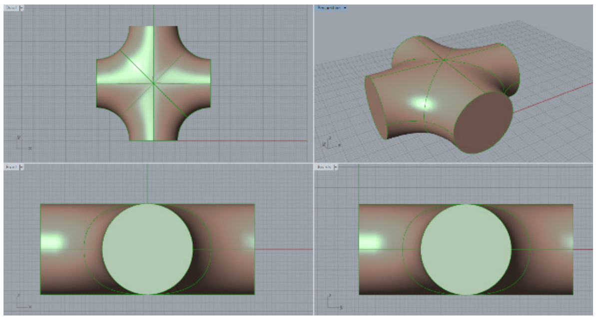

Figure 11. The smoothed geometry. We plug four of them together to create one void with the CC structure.

We can reach an arbitrary degree of continuity C^k for $k \in N$ but we are restricted to the technical borders of numeric calculations. In figure 12 we image the CC structure with the smoothing step in two different deg–rees of continuity.

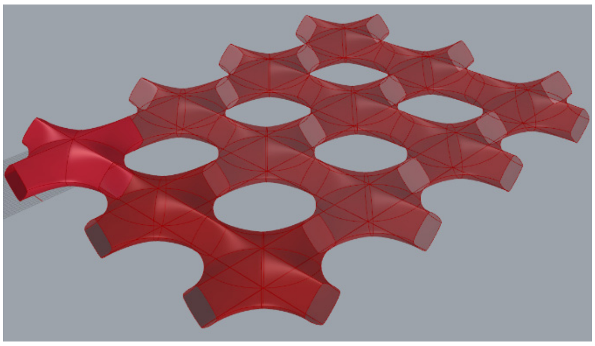

Figure 12. Hollow body with C^3-continuity.

The name Cross Channel technology is still correct in a broader sense. The crossing cylinders are in general not circular but elliptic or round. So, we didn't harm the cylinder's definition. The geometry has changed, we cannot describe the whole structure with rotating semicircles and tori anymore.

A result is that the smoothed structure avoids possible problems in concrete deaeration. But we save less concrete. We want to illustrate this with the values of the second chapter. We saved there 24.8% of conc–rete in the initial, unsmoothed geometry and 27.4% of concrete in the smoothed one (with respect to the refe–rence block). If we again fix R_1 = 30 mm and h_0 = 50 mm, then we receive a value of 16.3%. This is far less and not optimal with respect to (7). The saving is nearly constant, even if we alter the degree of continuity.

A possible next move touches the question of the void's placing. We do not have to adhere at symmetric models like in figure 12, where the holes lie in a 2 × 3 grid. Another possibility is a comb structure. We illus–trate the idea in figure 13.

With the changed structure we disengage from cro–ssing cylinders. The voids are not placed on a square but a hexagonal grid. The stability is better if we place two comb layers one upon the other. The grid is not very good with respect to (7). In nature this geometry is used by bees in honeycomb.

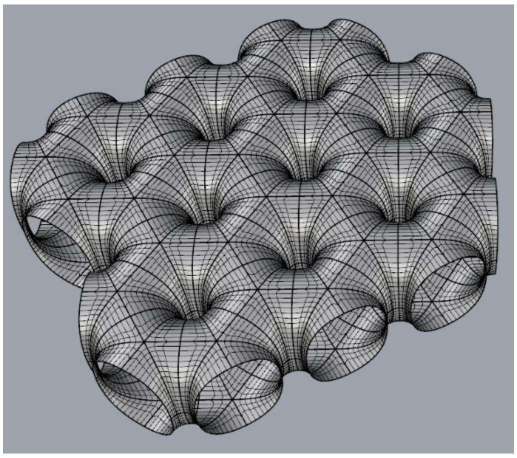

Figure 13. Change of the structure from blocks to combs.

4. CONCLUSIONS

We tried to find a way to save concrete in ceilings by placing voids in it. This was done in the central spots where the payload is low. The voids are made and filled with lightweight and sustainable recycled scrap paper. So we reduce dead load and save the environment.

The usage of CC structures made of scrap paper in ceilings and support structures is a very efficient way to save a large amount of concrete. By smoothing the complete outer surface, you can raise this effect even more and guarantee a uniform load distribution. The simulation with ANSYS validates our results. More detailed information concerning the CC technology can be found in [18].

In the next step, the smoothed geometry of the CC structures needs to be simulated in FEA software and concreted to compare their performance with the previous, non-smoothed one. We want to exhaust the placing of the void structure depending on the used concrete with respect to the maximal possible concrete saving. The upper bound are the standards in building industry to prevent a failure of the ceiling.

Starting by one large pillar-like torus we shrink the single void and connected it with more to get a greater structure. These interconnected voids save a great amount of volume. The load-bearing capacity is as high as a comparable ceiling made of solid concrete. Our geometry is smooth and causes no trouble in a one-step concreting.

The Cross Channel technology was optimized by smoothing the geometry. We raised the concrete saving higher than the previous, edgy structure. We fabricated these structures as half shells, merged them together and firmed them up. An exemplary calculation on a ceiling was installed in this paper.

We remark as final result: The structure of smoothed crossing channels, modelled with rotating semicircles leading to interconnected tori, is a very good way to fulfil the optimization task in equations (7) or (9) with respect to equation (8). A smooth structure spreads the stress uniformly and leads to a high load-bearing capacity. There already exists a way of creating hollow ceilings with CC structures whose performance is very high, even with a unsmoothed geometry.

In the further research, the smoothed structures should be firmed up to test their practical usability. There might be a problem with the air ventilation in the fabrication process but by using a fitting concrete. A changed grid type (like the combs in the paper) should also be a point of interest.

We used two forms (called male and female) with the technique of the overlapping joint to fabricate the corresponding half shells. It is possible to fabricate the half shells with only one form. For that, some methods like a tongue and groove system to fit similar objects together can be used. Due to a lack of time in the remaining project, we did not create a model of how to do it. However, this is another interesting point where you can save some material and money by renouncing a second form.

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ОПТИМИЗАЦИЈА ШУПЉИНА У БЕТОН–СКИМ СВОДОВИМА - ГЕОМЕТРИЈСКИ ПРИСТУП

К. Ноак, М.Ф. Ајхенауер, Д. Лордик

Задатак смањења потрошње материјала у грађевинској индустрији је хитан. Уштеда бетона чува природно окружење и новац. Да би се смањила потрошња бетона у зградама дизајнирамо шупља тела у конструкцијама сводова. У процесу слободне геометријске оптимизације ограничавамо се на оне облике који се могу произвести у полу-шкољкама. Наш главни циљ је најбоља размера уштеде у односу на ограничења процеса градње. Показали смо неке прихватљиве облике и касније се усредсредили на боље могућности, прелазне канале. Корак стварња прелазних форми како би се избегле оштре ивице који узрокују концентрацију напрезања још више ће допринети уштеди бетона. Вредноване су примене предложених решења у техничким апликацијама сагласно неким питањима, као што је проветравање бетона или ефектно прелажење у процес производње.